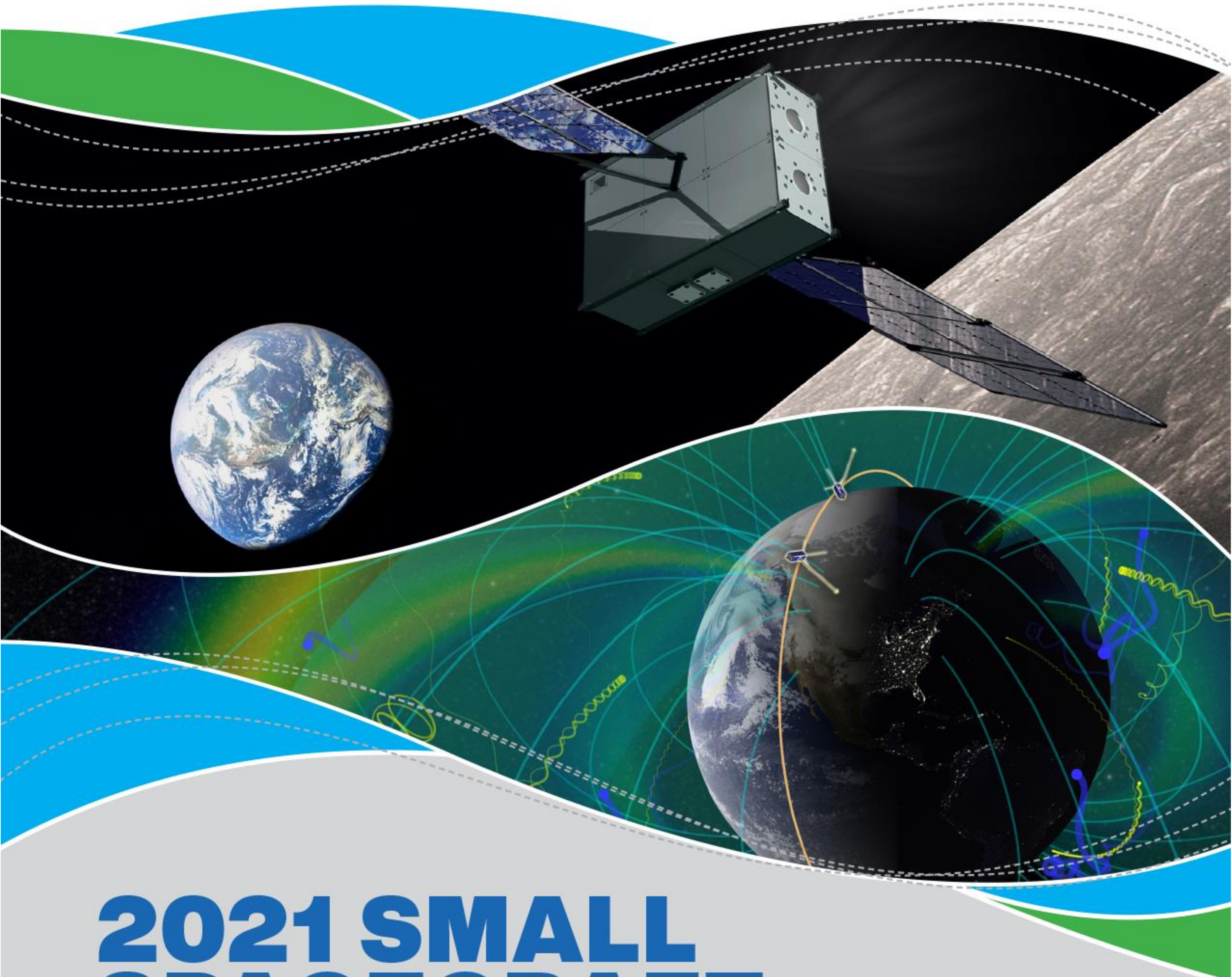
National Aeronautics and Space Administration



2021 SMALL SPACECRAFT VIRTUAL FORUM

March-May 2021

NOTE: This document summarizes results from the 2021 NASA SmallSat Virtual Forum. It is for informational purposes only and does not specify Agency plans or directives.

2021 SMALL SPACECRAFT VIRTUAL FORUM ORGANIZING COMMITTEE

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Any questions regarding the content of this report can be directed to Florence Tan (florence.w.tan@nasa.gov).

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Executive Summary

The 2021 National Aeronautics and Space Administration (NASA) SmallSat Virtual Forum brought scientists, managers, and engineers together to share challenges, lessons learned, and best practices regarding the formulation and execution of SmallSat missions. The forum consisted of five meetings, including an introductory meeting (Day 0) to share the SmallSat perspectives of the various NASA directorates, divisions, and centers. The remaining four meetings (Days 1-4) were dedicated to interactive open-forum workshop sessions of individual discipline-focused groups with an average participation of 33 per individual group. The results from Days 1-4 are summarized below.

On Day 1, the workshop sessions focused on the proposal phase and Pre-Phase A. Workshop participants strongly agreed there are three contributing factors for a successful project: a sound management plan, an understanding of the schedule and cost reserves, and careful evaluation of internal processes. They also identified four major project management challenges: (1) confusion about how NASA views risk and cost margins in SmallSat/CubeSat proposals, (2) a lack of publicly available cost models for Class D missions, (3) difficulty in identifying where to take 'extra' risks in the proposal, and (4) organizational structures that complicate staffing efforts for proposal development.

Clear definition of science goals and objectives is key to determine whether a mission is implementable as a SmallSat. These definitions help the science team and systems engineers to plan a mission that achieves compelling science, given the limitations of state-of-the-art technology for payload and spacecraft bus systems. Industry is constantly improving capabilities that could enable new missions, but this information may take time to reach potential Principal Investigators (PIs). NASA could facilitate information exchange by providing a central repository that contains the information in a standard format. In addition, the SmallSat community could benefit from NASA-provided proposal examples or proposal templates to enhance the quality of submitted proposals. The examples and templates would also help organizations without access to NASA center resources or experienced personnel to understand how to produce a winning proposal—potentially enabling new organizations to compete.

In terms of Safety and Mission Assurance (SMA), projects classified as Class D and below can be much more challenging than projects at Class C and above because the team will have to rely on focused understanding and management of risks and engineering judgment instead of defined, traditional practices. SMA sessions identified the need for NASA-provided resources to help projects with risk management. Missions can also benefit from available tools when preparing proposals, but these tools are not well advertised. For example, NASA centers have developed internal capabilities such as SmallSat design laboratories, but information about these capabilities is not readily available to the public. Workshop participants suggested that NASA sponsor a central location to promote these tools and capabilities.

Workshop sessions on Day 2 focused on project development cycle phases A, B, and C. Workshop participants tended to favor the two-step Phase A mission implementation process for SmallSats if: (1) the first step was simplified to reduce the number of resources needed and increase participation, and (2) the second step was adequately funded to ensure proper mission formulation. In addition, the group identified a need for NASA to establish a PI forum to encourage knowledge sharing in the SmallSat community.

Tailoring of documents is common for SmallSat missions and workshop participants identified a minimum set of required project-level documents: a master schedule, project plan, interface control documents (ICDs), and requirements. Reviews and configuration management processes should also be tailored to reduce the burden on SmallSat teams. The best solution may vary among projects and should be determined by considering a project's schedule, budget, team size, and risk posture. Complete and

concise documentation helps guide the team, especially when staffing changes occur. Tailoring of requirements management is also typical with projects carrying Level 1 and Level 2 requirements, but lower-level requirements are handled differently depending on the mission. Often, subsystem leads develop requirements based on Level 2 requirements. Ideally, a subsystem lead should construct a specific set of comprehensive requirements, but most projects seem to carry only key requirements at the subsystem level.

The commercial market plays an important part in NASA SmallSat missions, but the market is still evolving, and multiple projects reported challenges and problems related to use of commercial products. Defective product deliveries, evolving ICDs, and significant schedule delays were among the top three challenges. Projects have also experienced negative changes in the quality and performance of commercial off-the-shelf (COTS) components and subsystems sourced from previously successful suppliers. As with any COTS product (and in fact, even non-COTS products), reliability is established by volume and customer feedback, so new COTS products will require time and an expanding user base to establish reliability. To help mitigate these risks, projects can request an engineering unit or similar setup to be delivered for testing to the project team ahead of time.

Finding launch opportunities is a challenge for SmallSat missions, since they often receive the manifest (including testing requirements) at a late stage in the SmallSat development process. This challenge is even greater for missions outside of Low Earth Orbit (LEO) that also must meet orbital debris requirements. Late manifest increases risk for mission success, but there are other aspects that could involve considerable risk and that teams may need help to identify and track. For example, CubeSat PIs often struggle to define a reasonable approach for managing and reporting risk, as well as determining mitigation expectations for risks. Many SmallSat/CubeSat missions could benefit if NASA provided resources to help projects with risk management.

Day 3 sessions targeted activities and lessons learned during system assembly, integration and test (I&T), and launch. Work undertaken in advance by the project manager (PM), systems engineer (SE), and technical leads can lay the groundwork to mitigate issues during this phase. The PM must manage schedule, budget, risk, and personnel resources to tackle the “unknown unknowns.” SmallSats often have strict delivery timelines, and the PM should strive to mitigate team members’ fatigue and maintain morale—including backfilling technical roles as needed. When planning the schedule, the PM should budget adequate time for testing (e.g., double the expected time) to allow for inevitable delays.

SE challenges frequently involve management and communication of risks among various mission stakeholders. The SE team, often composed of a single team member, should fully understand the top-level requirements to inform descopes. Missions should also test interfaces as early and as often as possible since documentation and models are not always correct. Sufficient time should be allocated for system-level testing to enable the team to react to issues and determine appropriate penalty testing.

I&T planning for SmallSat missions that are managed according to NASA Procedural Requirement (NPR) 7120.5 differs from that for missions adhering to NPR, 7120.8 (“Do-No-Harm,” or Institutional-Best-Practices projects)—especially with respect to the level of documentation, rigor of testing, descope options, workforce planning, and type of test facilities employed. Test teams for the 7120.8-governed missions tend to be smaller and team members may perform multiple roles including quality assurance; therefore, it is useful to involve experienced personnel who can make calculated decisions based on risk posture. NASA could benefit greatly from standardizing I&T and SMA processes for Class D missions since each institution tends to follow its own practices and the level of tailoring is not consistent.

Design, analysis, and testing need to incorporate worst-case environments, including those encountered before launch such as specific environmental tests and transportation. For example, a deployment test under gravity can be the worst loading condition for a deployable in comparison to conditions encountered in a low-gravity environment. Testing should be as flight-like as possible (even for subsystem-only tests). Thermal vacuum (TVAC) testing should be conducted using as much of the full system as possible. During testing, projects should capture as much information as possible, including important housekeeping data to identify performance trends and diagnose issues during testing and on orbit. Usually, the most important product generated by a satellite is its science data, but housekeeping data plays an important role for monitoring, diagnosing, and fixing spacecraft issues, should the need arise after launch. It is useful to include as much summary data in bit-flags as possible if all housekeeping data cannot be downlinked due to mission limitations. It is also beneficial to record as much data as possible during ground testing, since this ground test data can assist in troubleshooting on-orbit anomalies.

Effective Phase D ground system testing requires adequate equipment, knowledge, and resources to replicate the operational environment. Government, commercial, and academic organizations all provide ground system (GS) capabilities and services, but these services are diverse, awareness of such services is limited (which can impact mission planning), and the services are sometimes challenging to learn about and implement.

Workshop sessions on Day 4 focused on mission operations, sustainment, and closeout. Establishing the first contact and successful communications remain a major challenge for many SmallSat missions. Best practices to mitigate communications issues include designing the radio to turn on automatically without receiving a signal from the ground, carrying backup communication systems, planning for access to backup ground stations, and practicing commissioning activities with both primary and backup systems ahead of time. Initial contact can be more challenging for higher frequency radios, which often require pointing control.

Lessons learned that increase likelihood of SmallSat mission success include the addition of simple sensors including diodes and cameras, which help identify, diagnose, and mitigate anomalies. Another potential mission-saving practice is to implement a flexible design that allows operators to request more detailed telemetry for each subsystem, if needed for verification or fault detection. In addition, carrying out regular system reboots can help clear issues in the avionics.

While technical and programmatic issues still exist, CubeSat/SmallSat capabilities are constantly improving, and it is becoming more common for SmallSat missions to remain operational beyond their mission lifetimes. Options to receive additional Phase E funding vary greatly amongst projects and divisions at NASA and clear guidance and a responsive process are urgently required. Likewise, ready access to funding for Phase F activities is required to optimize the returns from missions.

Another common challenge PIs face involves processing, storing, and sharing of mission data. Guidance from NASA on data standards and the implementation of best practices regarding data processing, storage, and sharing (along with templates and examples) would benefit SmallSat missions. Leveraging commercial cloud solutions for data storage and processing creates major efficiencies, particularly for collaboration and sharing of data; however, some program restrictions within NASA prohibit these options.

The NASA SmallSat community is a large group of passionate and enthusiastic scientists, managers, and engineers reimagining ways to reveal the Universe's greatest's secrets utilizing this disruptive platform, but each project team cannot operate in isolation. This forum highlighted the importance of sharing challenges, lessons learned, and best practices across missions. Participants encouraged NASA to continue its support and provide platforms for community members to learn from each other, and suggested the Agency create a SmallSat mentoring program and institute a regular PI forum. Workshop participants also gained awareness of industry products and services, including user experiences—knowledge that will enrich the NASA SmallSat community and enable future mission success.

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1. Introduction

1.1 Purpose and Scope

This document summarizes the results from the 2021 NASA Small Spacecraft Virtual Forum held from March-May 2021. The purpose of this virtual forum was to facilitate community learning through the sharing, exchange, and collection of experiences with small satellite mission development and execution across all NASA mission areas.

1.2 Forum Goals and Format

Designed to inspire frank and open discussions amongst participants, the forum aimed to establish and refresh best practices, solve individual and common mission problems, identify challenges along with possible solutions, and promote the promising future of SmallSats. Forum participants included principal investigators (PI), project managers (PM), and systems engineers (SE) of current and recent NASA-sponsored small spacecraft missions; NASA leaders; and program managers and executives involved with small satellites. Discussion topics covered the entire mission life cycle from concept formulation and proposal development; through construction, test, launch and operation; to end-of-mission, data archiving, and outcome reporting.

The first day of the forum on March 25, 2021 (Day 0) featured an opening plenary session. The first part of this session was dedicated to a general introduction of current NASA activities, organizations, and plans related to small spacecraft missions, highlighting recent science and technology demonstration successes, and presenting feedback from industry vendors. The second part of the session provided information targeted toward new PIs, PMs, and SEs, including what to expect after a proposal is accepted and advice for mission teams as they begin their newly selected missions. Chapter 2 of this report summarizes the roles and responsibilities of NASA Headquarters entities involved in SmallSat efforts and the NASA SmallSat opportunities that were reviewed during the first day of the forum.

Forum participants convened again every Thursday in April (Days 1-4) to discuss topics pertaining to a segment of the SmallSat mission lifecycle. Two consecutive forum sessions (Session A and Session B) were held each Thursday, with each session consisting of multiple discussions held in parallel on a variety of topics related to a segment of the mission lifecycle. Discussion moderators collected the findings and reported to the entire forum at the end of each session. Chapters 3-6 of this report detail the findings from forum discussions on Days 1-4. Subsections within each chapter describe the various session discussions, and key challenges and lessons learned gleaned from each discussion are organized in tables.

On May 6, a final NASA-only session was held to provide an opportunity for a deeper examination of the major lessons learned and challenges shared by forum participants. The important information derived from this workshop will inform and guide NASA's small satellite efforts moving forward.

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2. NASA SmallSat Organizations and Opportunities (Day 0)

On the first day of the workshop a representative from each NASA Headquarters organization involved in Agency SmallSat efforts gave a brief presentation outlining the organization's roles and responsibilities in the SmallSat community. The relationships between these organizations are depicted in Figure 1. The roles and functions of the various NASA Headquarters organizations regarding SmallSat activities are described in Table 1. Table 2 details the SmallSat programs and opportunities that exist within each Mission Directorate. These programs are also depicted as green boxes in Figure 1. When possible, the first column of Tables 1 and 2 includes a link to the organization's workshop presentation.

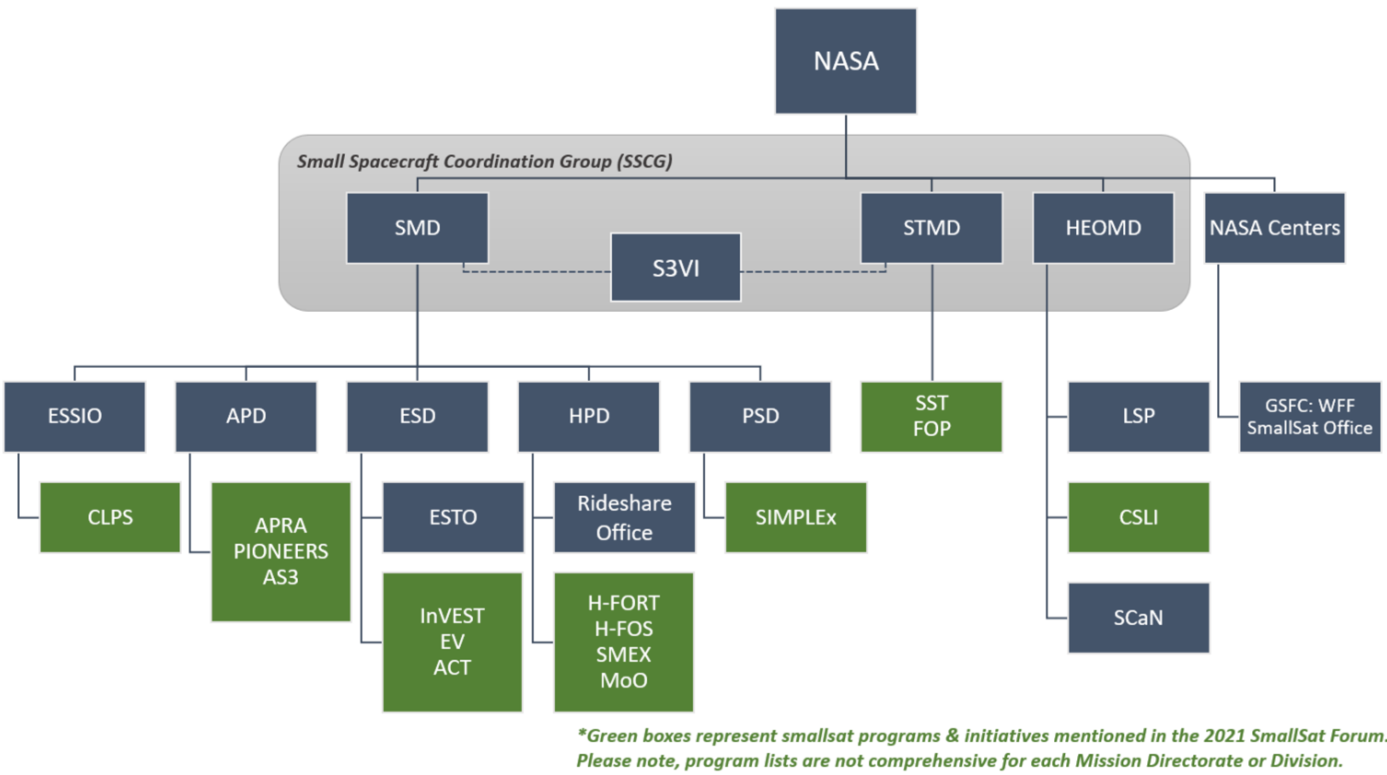

Figure 1. Organizational Chart of NASA SmallSat Organizations and Associated SmallSat Programs and Opportunities

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Table 1. SmallSat Roles and Functions of Various NASA Headquarters Organizations

NASA Headquarters Organization	SmallSat Roles and Functions
Science Mission Directorate (SMD)	• Manages SMD divisions (listed in Table 2) • Enables the launch of small satellites for faster collection of scientific data at a fraction of the cost of larger scale missions
SMD RideShare Office	• Formed at the direction of SMD policy SPD-32, Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Secondary Payloads Rideshare, to develop standard rideshare processes for SMD • The office's goal is to provide a single point of contact for SMD rideshare-related inquiries for NASA Centers and external partners, to maintain overall knowledge and tracking of rideshare activities for SMD missions, and to ensure optimal use of excess launch vehicle performance to obtain maximum science on SMD missions • Located within the SMD Heliophysics Division, but supports all SMD divisions
Small Spacecraft Coordination Group (SSCG)	• Formed to advise the SMD, Space Technology Mission Directorate (STMD), and Human Exploration and Operations Mission Directorate* (HEOMD) Associate Administrators on strategy to inform SmallSat cross-agency initiatives, policies, and programmatic scope • Guided by recommendations from the National Academies Achieving Science with CubeSats report and strives to meet the goals set forth in NASA's Strategic Plan • Responsible for coordinating, producing data products, reviewing agency and government documents, and serving as a representative for the agency and SMD regarding SmallSat matters
CubeSat Launch Initiative (CSLI)	• Provides access to space for CubeSats developed by NASA Centers and programs, educational institutions, and non-profit organizations. • Provides CubeSat developers with a low-cost pathway to conduct missions supporting science, exploration, technology development, education, or operations efforts
Small Satellites and Special Projects Office	• Located at Goddard Space Flight Center (GSFC) • Supports the Heliophysics Division's Heliophysics Flight Opportunities for Research and Technology (H-FORT) program and the Astrophysics Division's Astrophysics Research and Analysis (APRA) and Pioneers programs • Provides "light touch" mission management (i.e., facilitates status reporting between PIs and NASA Headquarters, maintains a portfolio database, etc.), grants management, engineering, and project support as necessary and requested, and insight into the SmallSat community based on previous mission experience
Small Spacecraft Systems Virtual Institute (S3VI)	• Enables clear communications and coordination regarding small spacecraft activities across NASA • Provides the U.S. SmallSat research community with access to mission-enabling information • Maintains engagement with small spacecraft stakeholders in industry, government, and academia.
Space Communications and Navigation (SCaN) Program	• Manages and directs the facilities and services provided by the Deep Space Network (DSN) and Near Space Network (NSN), including the Tracking and Data Relay Satellites (TDRS) • Advancing a strategy to transition to commercial services
Space Technology Mission Directorate (STMD)	• Expands the ability to execute unique missions through rapid development and demonstration of capabilities for small spacecraft applicable to exploration, science, and the commercial space sector

**As of fall 2021, HEOMD has divided into two separate Mission Directorates: Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD).*

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Table 2. SmallSat Programs and Opportunities Offered by NASA Mission Directorates

Organization	Opportunities offered
SMD	

[Planetary Science Division (PSD)]	• Small Innovative Missions for Planetary Exploration (SIMPLEx):
	  ○ Supports the formulation and development of science investigations that require a spaceflight mission that can be accomplished using small spacecraft
	  ○ SIMPLEx-1 was in 2014, followed by SIMPLEx-2 in 2018. The next SIMPLEx is to be determined.
	  ○ PSD is committed to providing rideshare opportunities when possible on future launches

[Astrophysics Division (APD)]	• APRA:
	  ○ $5M budget allows about one new CubeSat/year
	  ○ First CubeSat launch was in July 2018, with the next launch scheduled for Sept 2021
	  ○ Primarily 6U
	• Pioneers:
	  ○ A new class of small missions offered for the first time in Research Opportunities in Space and Earth Science (ROSES)-2020, $20M maximum PI cost cap
	  ○ Includes SmallSats, CubeSats >6U, major balloon payloads, and modest International Space Station (ISS)-attached payloads with a $20M cost cap, not including launch
	  ○ Solicited through ROSES; Relieves burden of writing full Explorers Mission of Opportunity (MO) proposal (ROSES 2020 Amendment D.15).
	• Astrophysics Science SmallSat Studies (AS3):
	  ○ 2018 (9) and 2019 (8) paper studies (~$100K each) of <$35M SmallSats as possible Explorer MO

Heliophysics Division (HPD)	• Heliophysics Flight Opportunities for Research and Technology (H-FORT):
	  ○ 2021 proposals due February 24, 2022
	  ○ Allows CubeSats and SmallSats up to 27 U, including constellations
	  ○ Explicitly includes both science and science-enabling investigations
	  ○ Increased allowed duration of mission (up to five years)
	  ○ Requires a "keep-alive" budget for up to 2 years
	  ○ Requires gate reviews and Key Decision Points
	• Heliophysics Flight Opportunities Studies (H-FOS):
	  ○ Competed for the first time this year
	  ○ About $100k for pre-formulation studies
	• Additional HPD SmallSat Opportunities:
	  ○ Missions of Opportunity (MoO) and Small Explorers (SMEx)
	  ○ Targeted technology demonstration opportunities
	  ○ Other major HPD Announcements of Opportunity individually evaluated for feasibility of accompanying MoO (e.g., Interstellar Mapping and Acceleration Probe [IMAP])

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Organization	Opportunities offered

Earth Science Division (ESD)/Earth Science Technology Program (ESTO)	• Advanced technology initiatives:
	  ○ Advanced Component Technologies (ACT): Critical components and subsystems for advanced instruments and observing systems
	  ○ In-Space Validation of Earth Science Technologies (InVEST): On-orbit technology validation and risk reduction for small instruments and instrument systems
	• Instrument Incubator Program (IIP): Earth remote sensing instrument development from concept through breadboard and demonstration
	• Advanced Information Systems Technology (AIST): Innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products
	• Decadal Survey Incubation (DSI): Maturation of observing systems, instrument technology, and measurement concepts for planetary boundary layer and surface topography and vegetation observables
	• Earth Venture Opportunities:
	  ○ Earth Venture-Mission (EVM): Complete, self-contained, small missions (about four years)
	  ○ Earth Venture-Instrument (EVI): Full function, facility-class instruments on Missions of Opportunity (MoO) (about three years)

Exploration Science Strategy and Integration Office (ESSIO)	• Commercial Lunar Payload Services (CLPS): An innovative service-based, competitive acquisition approach that enables rapid, affordable, and frequent access to the lunar surface via American commercial entities. CLPS launches are provided via the CLPS provider (not the NASA Launch Service Program, LSP) and approved/licensed by the Federal Aviation Administration (FAA) and other agencies (not NASA).
STMD	

Small Spacecraft Technology (SST) Program	• Small Spacecraft Technology Program: expands the ability to execute unique missions through rapid development and demonstration of capabilities for small spacecraft applicable to exploration, science, and the commercial space sector.
	  ○ SST is executed as a research and technology program, managed in accordance with NPR 7120.8A NASA Research and Technology Program and Project Management Requirements
	  ○ SST spans the heart of the Technology Readiness Level (TRL) spectrum with both Technology Development (TRL 3 to 5) and Technology Demonstration (TRL 6 or 7) projects. Technology Demonstration projects test technologies in relevant environments on both the ground and in space.
	  ○ Project Managers execute projects at academic institutions, in private sector, NASA Centers, or as public-private cooperative agreements.

Flight Opportunities Program	• Flight Opportunities Program: facilitates rapid demonstration of promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital testing with industry flight providers
HEOMD	

Advanced Exploration Systems (AES)	• For its internal SmallSat solicitation process, AES engages directly with NASA Centers and NASA Jet Propulsion Laboratory (JPL) through their assigned AES points of contact.
	  ○ Project Polaris Initiative:
	    ▪ New initiative to help meet the difficult challenges of sending humans to the Moon and Mars
	    ▪ Focused on filling high-priority capability gaps and on infusing new technologies into human exploration flight programs
	    ▪ Includes flight experiments and risk reduction activities to rapidly mature critical technologies
	    ▪ Consists of small teams and early career employees, which enables the strengthening of skills, gaining hands-on experience, and learning
	• AES also offers external SmallSat solicitation opportunities:
	  ○ Next Space Technologies for Exploration Partnerships (NextSTEP) can include partnerships with industry, academia, and some NASA Centers and JPL

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3. Pre-Phase A Concept Studies and Proposals (Day 1)

The first set of workshop sessions focused on the proposal phase during Pre-Phase A. During this segment of the mission lifecycle, the proposal team performs concept studies and develops and delivers proposals, setting the stage for the rest of the mission's development and implementation. Session participants discussed several topics including project management, systems engineering, the NASA Headquarters Announcement of Opportunity (AO) process, characteristics of a winning proposal, safety and mission assurance, and mission design tools and resources. The information captured in this chapter will be useful to personnel involved in SmallSat proposal development and management efforts.

Workshop participants strongly agreed there are three contributing factors that enable a successful project: a sound management plan, an understanding of the schedule reserve relative to the cost reserve, and careful evaluation of internal processes. During the project management session, participants discussed four major challenges: (1) confusion about how NASA views risk and cost margins in SmallSat/CubeSat proposals, (2) lack of publicly available SmallSat/CubeSat cost models for Class D missions, (3) identifying where to take 'extra' risks in the proposal, and (4) organizational structures that complicate staffing efforts for proposal development. Participants noted that a publicly available cost model for SmallSats and/or CubeSats would be beneficial.

To help guarantee success, a project should emphasize technical rigor up front and obtain commitments from personnel with the right expertise. Clearly defining science goals and objectives is also crucial in the beginning stages of a project. Session participants held an excellent discussion on the balance of letting science drive implementation versus implementation driving science. Since SmallSats/CubeSats are more constrained than larger missions, communication between the science team and systems engineers is vital to ensure mission objectives are scoped properly and implementation is feasible. Keeping up with the capabilities of industry and new technologies in development can be a challenge for the SmallSat community since the landscape is changing so quickly. NASA could assist the community by determining standards for recording heritage/technology readiness level (TRL) across agencies and establishing databases to maintain current information.

The ability to accommodate rideshare flexibility can be key for a winning proposal and some PIs have the perception that it is more important than the mission's science objectives. PIs are not sure how to be ready for any ride and are concerned that NASA will view use of an externally provided ride as an increased risk. If the PI elects to use a ride or a host external to NASA, there is no binding agreement, and the commercial partner can change costs or plans. If NASA funds the ride/host, the proposing PI does not know which vehicle will be used. Participants also expressed concern that increased requirements from the Federal Communications Commission (FCC) for propulsion could effectively kill the CubeSat program.

Succinctly defining how a mission will yield compelling, relevant, and adequately identified science or technology advancements is key to crafting a winning proposal. Proposers should link mission objectives to NASA's strategic plan and proper decadal surveys, focus on the primary science goal, and define science margins upfront. Not all PIs have the same access to proposal resources, including templates mirroring past successful proposals. PIs without access to NASA center proposal resources may unfairly and unintentionally experience reduced chances of winning. NASA should consider providing publicly available boilerplate examples or proposal templates to benefit the wider PI/PM community engaging in proposal writing.

During the safety and mission assurance session, participants described the distinctions among the NPR 7120.5 Class D, NPR 7120.8, and "Do No Harm" SmallSat risk classifications. Starting from the "Do No Harm" requirements, SmallSat projects should assess major risk areas across the project to identify where to apply additional safety and mission assurance processes effectively and to assure mission reliability. Risk assessment for projects at Class D and below can be much more challenging than for projects at Class C and above because such missions must rely on engineering judgment and focused understanding and management of risks instead of broad, traditional practices. Projects at Class D and below should avoid the temptation of applying Class A-C project practices that involve significant component-level efforts, since doing so will almost certainly reduce the ability to complete system-level testing and resolve problems due to the limited resources of projects at Class D and below.

Workshop participants agreed that the best way for a PI to choose which design lab to work with is to contact each lab individually and assess lab capabilities on a case-by-case basis. They also agreed that even in early-stage mission design efforts it is important to: (1) document assumptions and models behind the design products, and (2) make sure that modeling and simulation fidelity suffice to avoid significant budget and schedule overruns later in the project lifecycle. The SmallSat community could benefit from proactively using available mission design tools and sharing feedback about the usefulness of such tools. NASA could aggregate these tools under the current S3VI Mission Design tool webpage, including some lesser-known tools discussed during the session.

3.1 Project Management (Day 1, Session A1)

Session overview:
This session focused on the project management aspects of the proposal phase during Pre-Phase A. Topics discussed include proposal reviews, staffing, schedules, and budgets.

Session participants unanimously agreed that a sound management plan, an understanding of the schedule reserve relative to the cost reserve, and careful evaluations of internal processes are important elements of a successful project.

The following major challenges were discussed during this session:

- Confusion about how NASA views risk and cost margins in SmallSat/CubeSat proposals
- A lack of publicly available SmallSats/CubeSats cost models that could be used, in particular, for Class D missions
- Identifying where ‘extra’ risks can be taken in the proposal
- Organizational structures that complicate staffing efforts for proposal development

The discussion clearly showed that the community would benefit from a publicly available cost model that is tailored to SmallSats and/or CubeSats. A session participant noted NASA has invested resources to develop a SmallSat/CubeSat cost model.

Session notes organized by challenges and lessons learned:

D1-A1.1	**<u>Challenge</u> or Lesson Learned:**	**There is confusion in the community about how NASA views risk and cost margins in SmallSat proposals.**
	Rationale:	Differing language in the draft AO compared to the final AO resulted in confusion for one breakout group attendee.

	Suggestions or additional comments:	– Class D Mission proposals need to include margins as these missions will be asked for descopes. – For Class D Missions, the assessment of the probability of success is important. PIs can employ several different approaches to determine the likelihood of mission success – At a minimum, missions need a 25% financial reserve. – Good margins in Pre-Phase A are important; without them, evaluators will consider a proposal as weak, and the perceived level of risk will be increased.
D1-A1.2	**Challenge or Lesson Learned:**	**There is a lack of publicly available cost models to use, especially for Class D Missions.**
	Rationale:	Estimating SmallSat/CubeSat mission costs adequately is essential to mission success.
	Suggestions or additional comments:	– There has been a struggle to some degree to adjust existing cost models for SmallSats and CubeSats. – It is unlikely that existing cost models can be extrapolated to use with smaller sized missions because the processes employed on SmallSats/CubeSats differ from those on larger missions. – Participants expressed a need for a publicly available cost model that is tailored to SmallSats and/or CubeSats. NASA is investing in building a SmallSat/CubeSat cost model. Ideally, this cost model will be made available to all.
D1-A1.3	**Challenge or Lesson Learned:**	**The key to successful partnerships is having a sound management plan.**
	Rationale:	The project management plan can be a vehicle to document carefully planned and agreed roles and responsibilities of project partners.
	Suggestions or additional comments:	– Projects should inspect the value proposition that a partner may bring to a proposal. – Budgets are lean, management teams are small, and having too many partners creates unnecessary complexities. – The reviewers will penalize proposals if they do not demonstrate that the PI knows how to manage partners.
D1-A1.4	**Challenge or Lesson Learned:**	**It is unclear where 'extra' risks can be taken in the proposal.**
	Rationale:	An advantage of using these smaller platforms is being able to take on more risk. However, it is unclear where that 'extra' risk can be taken. Perhaps cost is not the place to take the risk. If so, where are the right places for taking risk in a proposal?

	Suggestions or additional comments:	– One attendee mentioned that they have been expanding the science/observational risk but not the risks based on technical concerns (making sure everything is above a TRL 6). – A reduction in process controls and oversight will increase the perception of risk from reviewers and stakeholders. However, the real elevated risk will come from the items a mission is forced to use because of resource limitations or technology advancement (e.g., the new thruster technology you must use that has only been flown for two hours on-orbit, but is critical to the mission).
D1-A1.5	**Challenge or <u>Lesson Learned</u>:**	**At the proposal stage, it is critical to understand the schedule reserve relative to the cost reserve.**
	Rationale:	Delays in deliverables and milestone completions cause mission cost overruns.
	Suggestions or additional comments:	– It is important to understand what the critical path is and what schedule reserve to put on that critical path. In addition, it is important to assign a secondary and tertiary path that could be used. If you do not define those alternate paths, reviewers will assign weaknesses to the proposal during the schedule evaluation. – Do not underestimate how much time it takes for a vendor contract to be established. – A lot of deliverables from vendors are built to order, so projects need to include schedule margins on vendor deliveries because they can be notoriously late.
D1-A1.6	**<u>Challenge</u> or Lesson Learned:**	**In certain environments, there are organizational structures in place that make it difficult to staff proposal teams.**
	Rationale:	Fully staffed proposal teams are important to complete a high-quality proposal and submit it on time.
	Suggestions or additional comments:	– Staffing problems can be a function of organizational structure. For example, it could be difficult to staff proposal teams in an academic environment. – Partnering with others who have the necessary and relevant skills is critical.
D1-A1.7	**Challenge or <u>Lesson Learned</u>:**	**To develop a successful proposal, build and tightly manage a schedule while writing the proposal and ensure the submitted proposal is consistent.**
	Rationale:	Meeting the deadline to submit the proposal on time requires discipline.

	Suggestions or additional comments:	– It is important to build and tightly manage a schedule for the proposal submission. The PI or lead should not perform this task. – Make sure that everyone shows up to the meeting to discuss the draft and/or final version of the proposal — this practice will help ensure that proposals developed by larger proposal teams are consistent. – Do not overstate the heritage and TRL in the proposal — exaggerating about them does no good.
D1-A1.8	**Challenge or Lesson Learned:**	**To maximize your budget during proposal development, perform careful evaluations of why you are spending money on certain tasks.**
	Rationale:	Managing limited resources to develop a proposal requires resource management skills.
	Suggestions or additional comments:	– Do a thorough evaluation of internal processes to determine what warrants spending. – Ask, "what risk am I driving down by spending this money?" – Be cognizant of certain requests that will not necessarily drive the risk down.

3.2 Systems Engineering (Day 1, Session A2)

Session overview:
The focus of this session was the systems engineering side of the proposal phase during Pre-Phase A. Topics discussed included the degree of technical rigor necessary in this phase, the importance of scoping objectives and adhering to science goals while also proposing a project that is feasible in a SmallSat/CubeSat form factor, and staying abreast of new technologies and identifying space heritage of components.

All members of the session agreed that emphasizing technical rigor up front is key to starting a successful project. In addition, clearly defining science goals and objectives is also crucial in the beginning stages. There was also excellent discussion on allowing science to drive implementation versus implementation driving science; since SmallSats/CubeSats are more constrained than larger missions, this challenge is often a balancing act between the science team and systems engineers.

SMEs provide tangible, practical advice to help projects identify space heritage for parts and stay on top of new and developing technologies in the SmallSat world.

Session notes organized by challenges and lessons learned:

D1-A2.1	**Challenge or Lesson Learned:**	**Even though concept studies in Pre-Phase A are often cost- and schedule-constrained, it is critical to apply good technical rigor and the right expertise to get the project started on a strong footing.**
	Rationale:	The work done in Pre-Phase A sets the stage for the rest of the mission's development and implementation. Scoping technical budgets and requirements at this stage is critical to ensure project success.

	Suggestions or additional comments:	– Involving the most experienced and most technically rigorous personnel is crucial at the beginning of a project, when things are most amorphous. – Knowledge transfer from the proposal development team to the implementation team can be a challenge. If new team members are involved in implementation, there should be an information handoff so that the implementation team understands the assumptions made in the proposal stage. – Information transfer is crucial, but not all information is critical. Access to tools to share information is critical (Wiki, pages, etc.). – Co-location of the team is also beneficial. – Things work better when the same team carries through from proposal development to implementation. – Keeping the science team engaged in early formulation meetings will ensure the design will work properly and the mission will achieve its science objectives.
D1-A2.2	**<u>Challenge</u> or Lesson Learned:**	**Missions that use SmallSats and CubeSats are often more difficult to design and implement from an engineering perspective than large missions, since the technical capabilities "box" is smaller, constraints are tighter, and margins are limited.**
	Rationale:	Science teams are often not familiar with how technically constrained a SmallSat/CubeSat mission can be in areas including mass, volume, power, pointing, data rates, and Delta-V. Systems engineers must help the science team to formulate its objectives within the constraints of the flight system to ensure a mission can be successfully proposed and implemented.

	Suggestions or additional comments:	– Systems engineers must work with the science teams as early as possible to help the science team to scope their objectives properly and ensure implementation is feasible, while still meeting NASA goals
		– Defining technical objectives initially will help avoid tailoring the science to the implementation instead of vice versa. For example, ask:
		    o What do you want to observe?
		    o Where do you need to be in space to get these observations?
		– Industry moves fast. Keeping track of state-of-the-art is critical, though it requires a lot of work up front. A systems engineer with expert knowledge of the latest industry capabilities can be well positioned to scope the mission correctly with the science team.
		– It is important to understand exactly what the AO is. Trying to make something fit into a CubeSat can be difficult. A lot of work, cost, and risk go into the projects that try to fit into this platform but cannot.

D1-A2.3	**<u>Challenge</u> or Lesson Learned:**	**Keeping up with industry capabilities and new technologies in development can be a challenge for SmallSats since the landscape is changing so quickly.**

	Rationale:	The SmallSat "New Space" industry is arguably growing faster than any other space industry. This growth can be advantageous, but it can also lead to challenges because products are changing so quickly.
	Suggestions or additional comments:	– Systems engineers should try to maintain an awareness of the environment as much as possible. NASA support to establish standards for recording heritage/TRL across agencies or databases to record information would be helpful. – Establishing partnerships and relationships with commercial bus and component providers is also beneficial, as they have the tools and understand their components. The NASA point of view regarding incorporating industry and commercial partners in proposal development is changing. NASA now recommends use of the providers as a resource. As the need to use COTS grows, the need to establish close relationships with manufacturers does as well. – Examining roadmaps of upcoming technologies and decadal survey recommendations can help missions stay up to date on technologies. – Coordinating with others in the SmallSat community via conferences is also beneficial, as well as tracking technologies through social media.
D1-A2.4	**Challenge or <u>Lesson Learned</u>:**	**Ensure appropriate margins are accounted for in the Pre-Phase A proposal stage.**
	Rationale:	It is impossible to account for everything in the design during Pre-Phase A. Adequate margins are needed to account for uncertainty and growth. Managing margins is one of the most, if not the most, critical job of the systems engineer.
	Suggestions or additional comments:	– Detailed technical challenges are sometimes not fully addressed due to constrained resources during Pre-Phase A. – Margins are a proxy for your unknowns on the technical side. – If there is an unknown, extra margin can be used to mitigate potential issues, but make sure someone knows about the situation. – It is important to clearly examine the connections between the subsystems to make sure margin is available. o *Example:* An interplanetary mission has a significant amount of Delta-V and it looks like the approach is feasible. But a closer look at mass margin consumption indicates that the propulsion system might not give the required Delta-V anymore. It is not just how much margin is available, but what happens when that margin is consumed? What is affected?
D1-A2.5	**<u>Challenge</u> or Lesson Learned:**	**When a proposal includes technology development, it can be a challenge to identify and access knowledge regarding space heritage of various components.**

	Rationale:	The SmallSat/CubeSat industry is so large that it is difficult to track the status and heritage of new technologies. Getting clear, accurate information from component providers can be difficult. TRL definitions can be unclear and vary between different organizations, making it difficult to assess the readiness of a technology for implementation in a mission.
	Suggestions or additional comments:	– The SmallSat Parts On Orbit Now (SPOON) database can be a potentially helpful resource. – Another suggested resource is PMPedia—a growing database for part-level heritage information. Radiation test data is available on PMPedia and from the GSFC Radiation Data Base. – Contacting providers directly can help address this challenge. When communicating with providers, make sure to have a TRL definition chart available, given TRL standards are not the same everywhere.

3.3 Headquarters Process for Announcements of Opportunity (Day 1, Session A3)

Session overview:
This session focused on the NASA Headquarters process and policies for SmallSat opportunities including timelines, how the coronavirus (Covid-19) has affected the typical process, and potential mission concepts matching/mismatching with NASA Headquarters opportunities. Topics discussed include difficulty in getting CubeSat proposals funded and how to prepare for rideshares without knowing an orbit.

Participants discussed their expectations for AOs and NASA research announcements (NRAs) for opportunities that utilize CubeSats/SmallSats. They expressed a desire for NASA to clearly describe the proposal review process and the criteria for a winning proposal in the AO or NRA.

The ability to accommodate rideshare flexibility can be key for a winning proposal and some PIs have the perception that it is more important than the mission's science objectives. PIs are not sure how to be ready for any ride and are concerned that NASA will view use of an externally provided ride as an increased risk. If a PI elects to use a ride or a host external to NASA, there is no binding agreement, and the commercial partner can change costs or plans. If NASA funds the ride/host, the proposing PI does not know which vehicle will be used. Participants also expressed concern that increased requirements from the FCC for propulsion could effectively kill the CubeSat program.

Session notes organized by challenges and lessons learned:

D1-A3.1	**Challenge or Lesson Learned:**	**Whether the opportunity is an AO or NRA, there is uncertainty in how high the bar is on the review and whether small or large institutions are prepared to meet that bar.**
	Rationale:	Even for NRA/CubeSats, the review process is perceived to be onerous. Small institutions might not be able to rise to the challenge of the review, while large institutions struggle with lowering the expectations on a NASA Procedural Requirements (NPR) 7120.8 or a 7120.5 Class D mission.

	Suggestions or additional comments:	– NASA should make proposal review process and expectations clear in the AO/NRA. – NASA could allow for competitions with less onerous expectations.
D1-A3.2	**Challenge or Lesson Learned:**	**There must be a balance between flexibility and achieving groundbreaking science in writing a winning proposal.**
	Rationale:	Rideshare flexibility is key to a successful proposal, and is perceived as being more important than the science objectives. PIs are not sure how to be ready for any ride. PIs are also concerned that NASA will view use of an external ride as an increased risk.
	Suggestions or additional comments:	– NASA should provide generic requirements for classes of orbits. – NASA should provide information on Rideshare availability and how this availability will impact programmatic decisions on selection. – Issues around hosted payloads and rideshare: if the PI finds the ride or host, there is no binding agreement and the commercial partner can change costs or plans, but if NASA funds the ride/host, the proposing PI doesn't know which vehicle will be used. – Participants suggested that the science should fit the bus, not vice versa. This concept, if accurate, needs to be socialized.
D1-A3.3	**Challenge or Lesson Learned:**	**There is a concern that increased FCC requirements for propulsion could effectively kill the CubeSat program.**
	Rationale:	Many CubeSats do not include propulsion systems.
	Suggestions or additional comments:	– If propulsion is required, how reliable does the system have to be? – NASA should monitor the situation and advocate for CubeSat systems.

3.4 Characteristics of a Winning Proposal (Day 1, Session B1)

Session overview:
This session focused on how to compose a successful proposal. Participants discussed the most important content to be included in proposals, how to best learn from past successful proposals, the most challenging requirements, and practical advice to avoid common mistakes in proposal writing.

Many challenges were identified, including disparate access to templates of successful proposals and other resources and proposal writing guidance that commonly exist at NASA centers. Participants held different thoughts on challenges related to proposal requirements, but noted that requirements should ultimately differ by mission type (science vs. technology) and cost.

PIs/PMs could benefit greatly from a centralized resource to leverage templates and materials from previous successful proposals. Ensuring that proposers outside of NASA centers have access to such resources would benefit the wider PI/PM community engaging in proposal writing.

NOTE: This document summarizes results from the 2021 NASA SmallSat Virtual Forum. It is for informational purposes only and does not specify Agency plans or directives.

Proposal reviewers shared practical advice about how to avoid common mistakes and ensure a proposal is well put together.

Session notes organized by challenges and lessons learned:

D1-B1.1	**Challenge or Lesson Learned:**	**Succinctly defining how a mission will yield compelling, relevant, and appropriately scoped science or technology advancements is key to crafting a winning proposal.**
	Rationale:	Proposals tend to focus on answering evaluation criteria, and sometimes do not clearly state the purpose of the mission. Proposals from the small innovative missions for planetary exploration (SIMPLEx) program were cited as a notable example.
	Suggestions or additional comments:	– Linking objectives (science or technology development goals) to NASA’s strategic plan and appropriate decadal surveys is a great way to justify the mission. – Focusing on the primary science goal will help focus the proposal. Avoiding secondary or tertiary objectives will aid in keeping the proposal focused on the primary science objective. – Session participants also advised proposers to define science margins at the beginning of the proposal effort.
D1-B1.2	**Challenge or Lesson Learned:**	**It is difficult for PIs to find the support needed to access scheduling and program management experts, as well as navigate all the proposal requirements.**
	Rationale:	Smaller organizations often lack the experience and resources to support space mission proposal development, while larger organizations may enforce extensive processes and procedures that are designed for large missions and ill-suited for many SmallSat and CubeSat missions.
	Suggestions or additional comments:	– PIs without access to NASA center resources or resources of other similar large space mission organizations do not have the same guidance for the proposal process as proposers with such access, which potentially unfairly and unintentionally reduces their chance of winning. – Institutions without large space programs face the choice of having the same experienced PMs on multiple proposals, which may be seen as a risk in the evaluation, or using less experienced PMs, which is only an option for the smallest missions and makes it difficult to grow and maintain extensive PM expertise for larger mission. – SIMPLEx Program management is assembling lessons learned to figure out how what has worked well and what needs to change in this process.
D1-B1.3	**Challenge or Lesson Learned:**	**The characteristics of a winning proposal differ across NASA mission directorates and types of missions.**
	Rationale:	Different missions will have different requirements to demonstrate.

	Suggestions or additional comments:	– Proposals for technology demonstrations should sufficiently describe the compelling science the project will enable. It is also necessary to compare the new technology to the current state-of-the-art. – Given that technology advances quickly, a short development schedule plays an important role in technology demonstrations. – For technology proposals, it is beneficial to state whether there are other investors in the same technology. If there are not, highlighting this fact will demonstrate the unique benefit the mission would pose.
D1-B1.4	**Challenge or <u>Lesson Learned</u>:**	**PIs should leverage previous templates of successful proposals when writing new proposals.**
	Rationale:	The challenge is not all PIs have the same access to proposal resources, including templates mirroring past successful proposals.
	Suggestions or additional comments:	– The Pioneers Program successfully applied lessons learned from the Astrophysics Research and Analysis (APRA) Program, including keeping the length of proposals reasonably short and reducing the reporting requirements for successful proposals. – NASA should consider providing boilerplate examples or templates for budgets, schedules, data management and plans, etc.
D1-B1.5	**<u>Challenge</u> or Lesson Learned:**	**Proposal requirements for certain missions are very lengthy to address.**
	Rationale:	Several proposers noted that requirements for proposals, even at the lowest end of the cost scale, are continuously increasing, making for ever more complex and lengthy proposals.

	Suggestions or additional comments:	– Exact length of proposals seemed to vary greatly across participants' experiences and mission types. Participants noted that divisions could assess their proposal calls against those from other divisions to determine best practices and possibly streamline the proposal process. – Proposing for missions within Science Mission Directorate (SMD) can be unique in that you need to validate both science and technology, making for longer proposals. – From a review panel perspective, a longer proposal can have varying effects: o It could lead to selection bias for large institutions. o It can be hard for a reviewer to absorb all the information and present it accurately to the rest of the panel beyond broad impressions, especially considering the fixed time panels are allocated and that fact that proposals are becoming longer. o It is more difficult for other panel members to follow up on discussion if they only read parts of the proposal. – Participants also suggested that NASA should consider tailoring requirements for the mission type carefully.
D1-B1.6	**Challenge or Lesson Learned:**	**Ensuring that someone familiar with the content reviews proposals prior to submission will help avoid common mistakes in proposal writing.**
	Rationale:	This lesson learned emerged as a best practice that enables the most efficient use of mentors and outside expertise during the proposal development phase.
	Suggestions or additional comments:	– Proposers should start early and have other experts review to make sure the proposal's message and content are clear – Ensure the proposal does not contain spelling mistakes or ambiguous table references. – Ensure the proposal has a clear flow from beginning to end. – Cross check the proposal against all proposal sections and requirements specified in the solicitation.

3.5 Safety and Mission Assurance (Day 1, Session B2)

Session overview:

The focus of this session was the safety and mission assurance (SMA) side of the proposal phase during Pre-Phase A. This area may be more challenging than others because virtually all proposals use generic compliance-oriented language while mentioning a collection of NASA center and agency directives, standards, and policy documents. Also, review panels for NPR 7120.5 Class D projects are used to seeing such documents. It may take time to convince review panel members what an appropriate approach for SMA looks like for a streamlined Class D mission. Topics discussed during this session included how much SMA is the right amount, what to do about planetary protection and other "Do No Harm" concepts, and how to assure and make the case for mission reliability.

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The initial topic discussed concerned the different pertinent SmallSat risk classifications of NPR 7120.5 Class D, NPR 7120.8, and "Do No Harm". It was not clear whether most of the audience members were familiar with these classifications as they are formally defined in Goddard Space Flight Center (GSFC) documentation; however, they are not used broadly across the agency. The agency does not formally define any risk classification outside of 7120.5 Class D. During the session, the following distinctions among these risk classifications were summarized:

- NPR 7120.5 Class D: Class D missions are required to follow NPR 7120.5 for project management; mission failure after launch would constitute a NASA mishap. Minimum levels of mission assurance are required across the board, albeit using a streamlined approach.
- NPR 7120.8: These missions are required to follow NPR 7120.8 for project management; mission failure after launch would not constitute a NASA mishap. However, the stakeholder may expect a particular success rate across multiple projects, e.g., 85%.
- "Do No Harm": These missions are not required to follow any project management directive (although internally a mission may choose to follow 7120.8 or other similar document); mission failure after launch would not constitute a NASA mishap. The only requirement from outside the project is not to harm people, the public, the environment, or cause any collateral damage.

When the planetary protection topic came up, the participants agreed that the approach was straightforward. If there is a threat of contaminating a planetary body, then planetary protections apply, and should be covered in the proposal. The same conclusion was extended to the "Do No Harm" concept.

During the discussion, a key question was raised regarding how much safety and mission assurance should be applied. Then, participants discussed how to assure mission reliability and how to describe it in a proposal. Participants determined that the primary way to address these issues is to assess major risk areas across the project to identify where additional processes should effectively be applied. This assessment should first examine the "Do No Harm" (typically to a host platform or the environment, including debris environment) requirements, followed by selected mission assurance requirements and processes as discretionary resources allow. Missions may find it beneficial to use one of the available constrained mission prioritization handbooks, such as GSFC-HDBK-8007, NASA Goddard Space Flight Center's Mission Success Handbook for CubeSat Missions. Other organizations have similar helpful documents.

SMA processes for SmallSat missions and the presentation of such in proposals vastly differ from the generic descriptions and approaches employed for larger missions. Risk assessments for projects at Class D and below can be much more challenging than for projects at Class C and above because such missions must rely on engineering judgment and focused understanding and management of risks instead of broad, traditional practices. Projects at Class D and below should avoid the temptation of applying Class A-C project practices that involve significant component-level efforts, since doing so will almost certainly reduce the ability to complete system-level testing and resolve problems due to the limited resources of projects at Class D and below.

Session notes organized by challenges and lessons learned:

D1-B2.1	**Challenge or Lesson Learned:**	**How much SMA should one include in the mission itself and how much detail should be put into a proposal?**

	Rationale:	On the stakeholder side, "Do No Harm" requirements are essential, since they may dominate the entire SMA program for a tiny mission. On the proposer side, clarity about the SMA approach in a proposal is essential to avoid excessive conflict with the inheriting program office. Overstating the intended SMA approach and subsequently addressing SMA with an extensive waiver process later further propagates the problem of excessive and inappropriate requirements to small missions.
	Suggestions or additional comments:	– When releasing an AO in which a specific host opportunity is provided, the stakeholder organization should provide as much information as possible on host protection requirements. – Organizations proposing Class D missions and below should thoroughly account for and communicate the approach for not harming the host platform, while other mission assurance activities should be detailed and communicated in the proposal, as resources allow. – AOs for 7120.5 projects include extra allowable space in the Appendix to provide details. Projects adhering to NPR 7120.8 are generally proposed through the ROSES platform, which has not been fully updated for space mission proposals other than CubeSat, International Space Station (ISS) payload, and similar opportunities.
D1-B2.2	**Challenge or Lesson Learned:**	**Like other core "Do No Harm" or safety elements, planetary protection is essentially binary: if it applies, missions need to plan for it and describe the approach in the proposal—regardless of mission risk classification.**
	Rationale:	There are no exemptions for "do no harm" activities and they can be a showstopper if not performed or described in the proposal.
	Suggestions or additional comments:	Planetary protection requirements can prevent a mission from going forward; therefore, the approach toward addressing such requirements should receive significant attention in the proposal. The less detail addressed, the more likely outside help will be provided that may not be in synch with mission development.
D1-B2.3	**Challenge or Lesson Learned:**	**How do we establish reliability for small missions that do not have resources for practices that are assumed to establish reliability?**
	Rationale:	Traditional approaches to reliability are indirect and based on extensive, conservative quality requirements—many of which actually contribute very little to reliable operation. Highly constrained projects cannot afford the resources needed to implement requirements that do not actually affect mission reliability. Therefore, such projects must be driven by a focused understanding of the risks for the mission and fault-tolerance must be built into the design when there is limited space for redundancy, as opposed to an application of stringent process controls, extensive detail specifications and screening processes, and intense oversight.

	Suggestions or additional comments:	– Conduct a risk assessment to identify driving issues on mission life limits beyond consumables and established limited-life items. – Certain standard practices are a top priority to establish reliability for any mission, including thorough testing in the appropriate environment with reasonable margin and subsequent problem resolution, employing fault-tolerant and radiation-tolerant design practices, proper derating (which may mean making sure parts and components are used within their "sweet spots"), and peer review.

3.6 Mission Design Tools and Resources (Day 1, Session B3)

Session overview:
This session focused on mission design tools and resources used during the early formulation phase. Topics discussed included how to contact the various design labs at the many NASA centers and how a PI can choose the lab that best fits the mission needs.

Most design labs have their own institutional websites, and there is no single repository missions can use to access all these sites. Session participants suggested that the design lab points-of-contact (POCs) be listed on the Small Spacecraft Systems Virtual Institute (S3VI) webpage. Regarding the best way for a PI to choose which design lab to work with, the community agreed that it would be best to contact each design lab and assess it. Cost emerged as the most likely driver for selecting a design lab. The community acknowledged that funding is usually scarce in early formulation, even though each center may offer some flexibility.

The SmallSat community could benefit from proactively using available mission design tools and sharing feedback about the usefulness of such tools. Participants recommended that these tools be aggregated on the current S3VI Mission Design tool webpage, including some lesser-known tools discussed during the session.

Participants agreed that even in early-stage mission design efforts it is important to: (1) document assumptions and models behind the design products, and (2) make sure that modeling and simulation fidelity is sufficient to avoid significant budget and schedule overruns later in the project lifecycle. This practice was acknowledged to be a challenge, given the budget constraints early in a small spacecraft project; however, it should be possible to carefully design early-stage toolsets and processes and provide informal but comprehensive documentation requirements.

The following links relevant to this discussion were shared by session participants:
- Small Satellite Reliability Initiative (SSRI) knowledge base: https://s3vi.ndc.nasa.gov/ssri-kb/
- Wallops Flight Facility (WFF) Mission Planning Lab POC: benjamin.w.cervantes@nasa.gov
- Glenn Research Center (GRC) Compass Team POC: Steve Oleson, steven.r.oleson@nasa.gov.
- Compass team website is: https://www1.grc.nasa.gov/facilities/compass-lab/
- Langley Research Center (LaRC) Engineering Design Studio: https://eds.larc.nasa.gov/
- GSFC Exploration and Space Communications services: https://esc.gsfc.nasa.gov/services
- S3VI Mission Design Tools https://www.nasa.gov/smallsat-institute/space-mission-design-tools
- OpenMDAO: https://link.springer.com/article/10.1007/s00158-019-02211-z
- dymos: https://joss.theoj.org/papers/10.21105/joss.02809

Session notes organized by challenges and lessons learned:

D1-B3.1	**Challenge or Lesson Learned:**	**The more prepared a PI/team is coming into a design session, the more effective and efficient the process and the overall result are.**
	Rationale:	Increased PI preparedness allows time savings and enables a better focus on the final product the PI needs.
	Suggestions or additional comments:	PIs should: – Understand the mission requirements clearly – Provide clarity on the needed figure of merit – Understand that a mission design lab does not write the proposal; rather, the design lab provides an opportunity to mature the concept
D1-B3.2	**Challenge or Lesson Learned:**	**The best way for a PI to choose which design lab to work with is to assess each lab's capabilities on a case-by-case basis.**
	Rationale:	PI needs and funding availability may vary, and PIs should reach out to the different design lab POCs to discuss the specific mission concept development needs.
	Suggestions or additional comments:	– NASA should aggregate the POCs for NASA mission design labs on the S3VI website. – Every NASA mission design lab may have some flexibility in funding a concept of interest to that lab.
D1-B3.3	**Challenge or Lesson Learned:**	**The community seems not to have taken full advantage of exploring the available NASA (and non-NASA) mission design tools like the SmallSat Parts On Orbit Now (SPOON) database, Small Satellite Reliability Initiative (SSRI) knowledge base, and SatSearch.**
	Rationale:	There was a lack of response when session participants were asked to discuss the usefulness of the available NASA mission design tools.
	Suggestions or additional comments:	– NASA should actively encourage the community to test out the available mission design tools, like the SPOON database.
D1-B3.4	**Challenge or Lesson Learned:**	**There are some NASA mission design tools that are not well known.**
	Rationale:	Some of these efforts are relatively recent or not widely advertised.
	Suggestions or additional comments:	– Example tools include: o Glenn Research Center Multidisciplinary Design Analysis and Optimization (MDAO), an open-source framework for multidisciplinary design, analysis, and optimization: https://link.springer.com/article/10.1007/s00158-019-02211-z o dymos, A Python package for optimal control of multidisciplinary systems: https://joss.theoj.org/papers/10.21105/joss.02809 o GSFC Exploration and communication org: https://esc.gsfc.nasa.gov/services. POC https://esc.gsfc.nasa.gov/services. – NASA should aggregate the above tools on the S3VI mission design tool page or provide links to them.

4. Phase A, B and C Concept/Technology Development, Preliminary/Final Design, and Fabrication (Day 2)

The second set of workshop sessions focused on development cycle phases A, B and C. These phases typically include numerous activities, beginning with the Concept Study Report (CSR) and concluding with the Systems Integration Review of the mission. A total of eight topics were discussed in these sessions, including project management, systems engineering, the risk program, and launch opportunities. The information captured in this chapter can benefit projects as they implement missions and NASA management as it formulates policies.

Workshop participants tended to favor the two-step Phase A mission implementation process for SmallSats as long as: (1) the first step was simplified to reduce the number of resources needed and increase participation, and (2) the second step was adequately funded to ensure proper mission formulation. SmallSat missions do not always include a CSR as the culmination of the two-step mission implementation process; however, the idea of developing a CSR in the second step was viewed as favorable and necessary for the more complex missions. In addition, the group identified a need for NASA to establish a PI forum to encourage knowledge sharing between the PIs.

A successful mission starts with a good project plan. Tailoring documentation is important for SmallSats. The minimum set of required project-level documents is typically comprised of the schedule, project plan, interface control documents (ICDs), and requirements. Reviews and configuration management processes should also be tailored to reduce the burden on the team. The best solution may vary among projects and is determined by considering schedules, budgets, size of the team, and risk posture. Complete and concise documentation helps guide the team, especially when staffing changes occur. Merging reviews and holding more focused peer reviews are common successful approaches for small projects. Master schedules should be utilized for planning purposes and running “what-if” scenarios.

Communication is also key on SmallSat projects. It helps to have a team member or advisor well-versed in the science and engineering to ensure effective communication between the science and engineering teams. Open and honest communication among team members and employing a risk-based mindset are also critical to uncover problems and mitigate them earlier. Openly sharing potential pitfalls among project team members helps ensure that issues will be noted and addressed early, while the impact on resources is still relatively small.

The tailoring of documentation and processes is also needed on the technical side. Projects typically carry Level 1 and Level 2 requirements, but lower-level requirements are handled differently depending on the mission. Often, subsystem leads develop requirements based on Level 2 requirements. Ideally, the subsystem lead should construct a specific set of comprehensive requirements, but most projects seem to carry only key requirements at the subsystem level.

The commercial SmallSat/CubeSat market is still evolving, and multiple projects reported challenges and problems related to use of commercial products. Defective product deliveries, evolving ICDs, and significant schedule delays were among the top three challenges. To help mitigate these risks, it is recommended that projects request an engineering unit or similar setup to be delivered for testing by the project team ahead of time. Projects have also experienced negative changes in the quality and performance of COTS components and subsystems sourced from previously successful suppliers. As with any COTS product (and in fact, even non-COTS products), reliability is established by volume and customer feedback, so new COTS products will require time and an expanding user base to establish reliability. Companies or products that are less mature tend to have a greater risk of delayed deliveries or deliveries of products that are not ready for shipment.

The recent proliferation of LEO launch opportunities has helped meet demand for SmallSat launches, but it is still difficult to find a launch opportunity to some unique orbits and to find orbits beyond LEO that meet orbital debris requirements. Propulsion is often the key enabling technology to meet SmallSat mission requirements beyond LEO.

PIs struggle with defining a reasonable approach for CubeSat programs regarding the process for managing and reporting risk, as well as determining the risks they should expect to mitigate. Many missions could benefit if NASA provided resources to help projects with risk management.

Regarding licensing processes, projects must first understand their data and orbital requirements to start the iterative process to define downlink requirements, determine frequency allocation, select ground stations, and select radios. This process must occur as soon as possible to allow time for any unexpected occurrences during the licensing process. Projects should strive to prepare a complete application to avoid potential delays.

4.1 Project Management (Day 2, Session A1)

Session overview:
This session focuses on project management of a mission from concept development to fabrication. The first lesson learned discusses the tailoring of reviews to reduce burden on small teams. Many organizations have successfully implemented such tailoring, including merging the System Requirements Review with Preliminary Design Review (SRR/PDR) and combining the Critical Design Review with the System Integration Review (CDR/SIR). Tailoring of development processes should also include SmallSat configuration management. Such tailoring will depend on mission class and size of the team. A small team can be successful using a more agile solution, while a larger team working on a higher-class mission may benefit from a more formal configuration management (CM) process. Regardless of the CM system employed, the mission should strive for effective documentation, at a minimum on essential documents such as requirements, the project plan, concept of operations and interface control documents. Project documentation is especially important when the project suffers staffing changes, as it can preserve the continuity of the tasks and intent of the requirements. Another way to tackle staffing changes is to maintain personnel continuity on key areas such as project management and systems engineering.

Running an effective and efficient team is a common goal for all projects. To help with this aspect, it is beneficial to include someone versed in both science and engineering in the team (officially or unofficially) to improve communication, especially helping in the “translation” between science and engineering. Another way to improve efficiency is the utilization of an integrated master schedule (IMS) for managing schedule (and therefore budget). More than a tracking tool, an IMS is a planning tool that can help with “what-if” scenarios. Communication is another key area to enable efficiency. Project leadership should create and foster an environment fostering good communication, trust, and teamwork for mission success. Such an environment should encourage team members to speak freely. Project leaders should also attempt to identify team members with hidden agendas to better manage the team.

A common management strategy for small missions is to employ interns and students—often to promote career development/training or reduce development cost. This practice can be beneficial for a project if used wisely. Effective implementation needs to incorporate three key elements: the individual’s technical ability, task completion timeframe, and effective mentorship.

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Session notes organized by challenges and lessons learned:

D2-A1.1	**Challenge or Lesson Learned:**	**CubeSat projects have successfully deviated from the typical number of project reviews.**
	Rationale:	Reviews can add a significant amount of overhead and CubeSat schedules are already compressed.
	Suggestions or additional comments:	– For example, a project from academia adhering to NPR 7120.8, NASA Research and Technology Program and Project Management Requirements successfully compressed its review schedule to include two major reviews: o Combined SRR/PDR: conducted in the fourth month of the project, based primarily on detailed work on requirements and preliminary design accomplished during the proposal phase o Combined CDR/SIR: conducted at month 14, prior to major hardware construction
D2-A1.2	**Challenge or Lesson Learned:**	**It is important to streamline and use configuration management effectively.**
	Rationale:	Extensive configuration management practices can add burden on the team but result in only marginal benefits. A good balance must be maintained to obtain the main benefits of a good configuration control process.

	Suggestions or additional comments:	– Strive for minimum configuration management; a sophisticated configuration management system is not needed to be effective. First, determine who needs access to a particular type of information. For example, a NASA mission used a wiki page to collaborate with academia and industry since the NASA system was not accessible to external partners. – Use existing infrastructure, since building and learning new tools is expensive in terms of time and effort. In general, very few documents need to be put under typical configuration management, although some configuration management tools can serve as effective repositories to archive documents for future use/reference. As a minimum, consider including the project plan, requirements documents, concept of operations, and interface control documents under configuration management. – Configuration management may scale with the size and risk classification of the project. A small NPR 7120.8 project may be more agile using a wiki, while a larger team may benefit from a more formal configuration management tool to keep different parts of the team on the right track. – Regardless of how configuration management is employed, the implementation details should be documented in a standalone document or within the project plan.
D2-A1.3	**Challenge or <u>Lesson Learned</u>:**	**Good documentation and continuity of key team members are essential to effectively endure staffing changes**
	Rationale:	CubeSat projects often go through staffing changes that negatively impact development. As such turnover is unavoidable most of the time, there are some ways to help minimize the impact.
	Suggestions or additional comments:	– Well-written requirements and thorough documentation are essential to maintain knowledge between staffing changes. Including a rationale for each requirement is important since requirements can be hard to write well and are often misinterpreted. – In addition, it is important to maintain continuity in key positions such as the Project Manager and the Systems Engineer, since these individuals are exposed to many aspects of the development including but not limited to project formulation, trade studies, lessons learned, requirements, and risks.
D2-A1.4	**Challenge or <u>Lesson Learned</u>:**	**It is beneficial to include someone well-versed in both the science and engineering aspects of the mission on the team to improve communication**

	Rationale:	Scientists and engineers approach problems very differently. Projects do better when there are cross-discipline members of the team, who can "translate" between science and engineering.
	Suggestions or additional comments:	– Cross-discipline team members can fill official or unofficial roles such as Science Consultant, Senior Fellow, Project Scientist, Instrument Scientist, Instrument Systems Engineer, or Mission Systems Engineer. The key to communication is to explain the "why," so that both scientists and engineers understand the drivers behind requirements.
D2-A1.5	**Challenge or <u>Lesson Learned</u>:**	**The integrated master schedule (IMS) is a key tool for managing schedule (and therefore budget)**
	Rationale:	The IMS is not just a reporting tool, but rather an early warning system, and can help solve problems by enabling analysis of what-if scenarios. As budgets turn from planning to execution as a function of time, then cost reserves (if available) are employed to handle changes and mitigate risks/problems.
	Suggestions or additional comments:	– The IMS should be a living tool and be updated regularly over the lifetime of the mission.
D2-A1.6	**Challenge or <u>Lesson Learned</u>:**	**Employing interns and students can be beneficial for a project if such resources are used wisely.**
	Rationale:	Interns and students may be able to produce good work at a lower cost but require good mentorship and realistic assignments based on their capabilities and availability.
	Suggestions or additional comments:	– Development speed can be an issue for personnel who work on a project on a limited basis, such as interns and university students whose availability is constrained by the school calendar. Employing interns and students to accomplish component-level work has been successful even with summer or semester constraints.
D2-A1.7	**Challenge or <u>Lesson Learned</u>:**	**Project leaders need to create and foster an environment with good communication, trust, and teamwork for mission success**
	Rationale:	Small teams rely on good communication and trust in each other to execute. If a team member does not communicate well or cannot rely on other team members to do their part, the team works less efficiently.
	Suggestions or additional comments:	– Establishing a common goal for the whole team is important, so that everyone is working together in synergy. There should be clear lines of communication, all team members should be empowered to bring things up, and others on the team need to listen.

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4.2 Systems Engineering (Day 2, Session A2)

Session overview:
This session focused on systems engineering—from concept development to fabrication. Systems engineering encompasses many activities for a mission, but requirements management is one of the cornerstones of systems engineering. Requirements management is particularly challenging for small teams, which may not have the manpower to manage every typical requirement level. Regardless, the systems engineer should develop and maintain a good set of clear Level 1 and Level 2 requirements. The approach for successful management of lower requirements varies by project and organization, but typically subsystem leads manage their own requirements or at least key requirements derived from Level 2.

Efficient management of technical budgets is key on highly constrained SmallSat projects. This effort requires constant tracking of subsystems and is typically done at a higher level (systems engineering). Management of technical budgets is an area where projects could benefit from additional guidance from NASA.

The SmallSat/CubeSat market is still evolving, and multiple projects reported challenges and problems related to use of commercial products. Defective product deliveries, changing ICDs and significant schedule delays were the top three concerns. To help mitigate these risks, it is recommended that projects request an engineering unit or similar hardware to be delivered for testing by the team ahead of time.

Multiple challenges and lessons learned can be explored regarding software. The primary concern focused on development time required for software and how it is typically underestimated. Participants agreed that more time is needed to expand on the topic and capture more valuable information.

Session notes organized by challenges and lessons learned:

D2-A2.1	Challenge or Lesson Learned:	Early in the mission lifecycle, it is challenging to develop an appropriate set of requirements that will effectively guide the mission development.
	Rationale:	SmallSat projects need to spend adequate time defining requirements early in the mission lifecycle since significant costs can be incurred later in development if requirements are not defined and managed properly.

	Suggestions or additional comments:	– Projects need to formally develop Level 1 and Level 2 requirements. Level 1 requirements state the scientific effort that must be accomplished for mission success and are often referred to as the agreement between the project and the main stakeholders. Level 2 requirements capture the top-level decisions about how the mission will be implemented. – Level 1 and Level 2 requirements—including traceability—need to be formalized by the Mission Systems Engineer. – The formal development of lower-level requirements along with their traceability and tracking may not be appropriate for small satellite missions, but successful mission development requires capturing the performance decisions (requirements) at these lower (sub-subsystem) levels. – Different missions have accomplished the function of lower-level requirements (Level 3, 4, etc.) through informal requirement statements, which are tracked by subsystem leads or through structured interface control documents. – The science team and engineering team need to work together to scale down expectations and simplify projects to produce a set of achievable requirements for a SmallSat or CubeSat project.
D2-A2.2	**<u>Challenge</u> or Lesson Learned:**	**Allocating and tracking of technical resource budgets for SmallSat and CubeSat missions is challenging.**
	Rationale:	SmallSat projects usually need to manage highly constrained technical budgets. It is difficult to assign generous technical budget allocations to each subsystem. Technical budgets and margins are tracked at a higher level.
	Suggestions or additional comments:	Tracking at the system level requires inputs from across the development team. Management of technical budgets seems to be a weakness, and SmallSat and CubeSat projects could benefit from NASA guidance. Generally, technical budgets for small programs are tracked using a spreadsheet instead of a formal tool.
D2-A2.3	**<u>Challenge</u> or Lesson Learned:**	**Significant challenges and problems arise when working with subsystem vendors.**
	Rationale:	SmallSat missions are highly dependent on a still developing and rapidly evolving supply chain.

	Suggestions or additional comments:	– Problems reported most often include defective product deliveries, changing ICDs and significant schedule delays. Some participants reported that vendors provided completely non-functional equipment that would not even power up. – The SmallSat industry is perceived as being composed of small and new businesses that are unreliable at times. There can be a large gap between what businesses advertise and what is sold, and small satellite programs need to understand the potential risks associated with inexperienced vendors. – A suggested approach to help mitigate these issues is to request partial deliveries of mechanical and/or electrical prototypes or engineering units that can be integrated early into the mission flight or development hardware. – Given that CubeSats are largely composed of COTS components pulled together by small teams, working with the vendors and making them part of the team is one approach that has worked for some CubeSat programs. – Awareness about vendor quality and repeatability of products would be enable project teams to select the best offerings from the market. Disseminating this knowledge will require a coordinated effort to share vendor experiences and lessons learned among multiple users.

4.3 Headquarters Processes (Day 2, Session A3)

Session overview:
The focus of this session was the process used by NASA to interact with PIs post-award. Topics discussed involved the one- vs. two step award process, the value of a Step 2 Concept Study Report, NASA oversight requirements, and communication with the program offices. Early discussion centered around the proposal process and whether a one-step or two-step process was more appropriate for small satellites. The group tended to favor the two-step process as long as the first step was simplified, and the second step was adequately funded. Participants expressed some concern that a more involved, one-step process would be prohibitive to institutions with limited resources and would give more established institutions an advantage. Participating in this process is costly to the institutions and the probability for success is very low. The idea of working through a Concept Study Report (CSR) in Step 2 was seen as favorable and necessary for the more complex missions. PIs appreciate the opportunity to develop the technical details of a mission concept more fully before starting the development phase. The primary concern is obtaining the proper level of funding to do the study. There was also interest in obtaining more guidance on what the expectations are for such studies.

Appropriate level of NASA oversight is another concern. Some participants expressed resistance to having too much oversight when it came to formal reviews. Others thought it was reasonable to require some type of gate reviews, especially for the more complex missions. All agreed on the importance of having open and honest communication between the PI and NASA over the course of the project. Such communication could be structured in several different ways depending on the needs of the mission.

Participants recognized the need for NASA to establish a PI forum to encourage knowledge sharing among the PIs. The group discussed how PIs in organizations such as the National Science Foundation and the NASA Sounding Rocket Working Group share knowledge.

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Session notes organized by challenges and lessons learned:

D2-A3.1	**<u>Challenge</u> or Lesson Learned:**	**The more involved, higher-page-count, one-step proposals pose a challenge to institutions with limited resources.**
	Rationale:	It is costly for institutions to put together this type of proposal and the chances for selection are low.
	Suggestions or additional comments:	– NASA could utilize a two-step process that includes a simplified first step to allow a lower cost of entry and a funded second step to support further proposal refinements. Larger institutions with more access to resources are at a significant advantage with the more involved one-step process. STMD has demonstrated a two-step proposal process that involves 1-2-page Step 1 proposals and Step 2 proposals with low page count (10 pages) for $30M+ missions.
D2-A3.2	**Challenge or <u>Lesson Learned</u>:**	**Working through a Concept Study Report (CSR) phase is beneficial but requires adequate compensation for PIs.**
	Rationale:	There is value in being able to refine the mission concept and plan prior to entering the development phase, but it is costly to do these refinements.
	Suggestions or additional comments:	– NASA needs to provide adequate funding and time to complete a CSR. The four months and $40K provided for the last H-FORT CSR phase was not considered adequate. For more complex missions, it is vital to require this second step to show technical implementation details. There needs to be more clarity on what is expected for the CSR. Many projects can benefit from NASA-provided training for those new to the process.
D2-A3.3	**Challenge or <u>Lesson Learned</u>:**	**There is some concern with having too much NASA oversight when it comes to formal reviews for NPR 7120.8 missions.**
	Rationale:	Project teams are experienced enough to know what needs to be done and some institutions may not have the resources to address the imposed review requirements.
	Suggestions or additional comments:	– STMD is not requiring gate reviews, but their review structure for missions beyond LEO is more traditional and includes PDR/CDR-style reviews. STMD requirements for LEO missions are less traditional and involve a three-review set including a Mission Concept, Pre-ship, and Post Flight Review. Complex missions can benefit from having gate reviews. The set of gate reviews required for H-FORT (SRR, PDR/CDR, and Flight Readiness Review [FRR]) seem reasonable. SMD has perceived that PIs learn a lot by going through a formal PDR process. NASA should provide guidance for the gate reviews to the PIs.
D2-A3.4	**Challenge or <u>Lesson Learned</u>:**	**Open and honest communication between NASA and the PIs is a very important part of the process.**

	Rationale:	Open communication allows problems to be identified early so that they can be addressed in a timely manner.
	Suggestions or additional comments:	– Such communication allows both NASA and the PI to "get on the same page" with respect technical and programmatic risks. The communication can be structured in many different forms relative to mission needs—ranging from informal, quick conversations to a more structured cadence of weekly or monthly meetings.
D2-A3.5	**Challenge or Lesson Learned:**	**A PI network or forum would be helpful to the community.**
	Rationale:	PIs would be able to share experiences and obtain guidance on how to tackle various challenges they are facing.
	Suggestions or additional comments:	– The National Science Foundation (NSF) holds regular forums where the PIs present their mission progress to other PIs and interaction is encouraged. NASA's Sounding Rocket program has sponsored a PI-driven working group for many years, which could serve as a model for small satellite projects. There is also interest in having a forum available at all times, where commercial communication platforms could be leveraged.

4.4 Launch Opportunities (Day 2, Session A4)

Session overview:
This session addressed topics relating to launch opportunities for small spacecraft. Specific orbit and timeline constraints can be difficult to meet and costly for SmallSat projects that nominally rely on rideshare launch opportunities. Requirement definition is key when seeking a launch service because the industry is geared toward meeting specific requirements. Above low earth orbit, orbital debris requirements can become a driver for orbit requirements.

Session participants recognized a potential disconnect between the development timelines of small satellites and the launch timelines. Many of the CubeSat launch opportunities today utilize the International Space Station (ISS), but the ISS program will someday conclude. NASA Launch Service Program (LSP) representatives described their approach to ensuring continued access to space for small spacecraft and recognized that rideshare opportunities will likely continue to be the most common opportunity.

Session notes organized by challenges and lessons learned:

D2-A4.1	**Challenge or Lesson Learned:**	**The timeline of spacecraft development does not always line up with the launch timeline.**
	Rationale:	Multiple factors affect mission development timelines and launch vehicle timelines and often these two types of timelines conflict.

	Suggestions or additional comments:	– It was expressed that all the schedule resiliency is on one of the two timelines. It is usually costly to require a specific orbit at a specific time, rather than using more common launch opportunities. There is usually not a difference between the launch timeline for different sizes of CubeSats, but Class D and ESPA-class spacecraft timelines can differ. If a spacecraft is flying as a rideshare payload on a NASA launch, the launch timeline can be longer.
D2-A4.2	**Challenge or Lesson Learned:**	**It is difficult to find a launch opportunity to some unique orbits, and to find orbits that meet orbital debris requirements**
	Rationale:	As a secondary payload, SmallSat missions do not get to dictate the launch parameters and pairing with the right primary payload is required. This situation presents a big challenge for SmallSats that must be positioned in unique orbits. This problem can be aggravated when also considering orbital debris and re-entry requirements.
	Suggestions or additional comments:	– For orbits above LEO, such as geosynchronous transfer orbit, it is challenging to satisfy orbital lifetime requirements by passively deorbiting. It is important to define the orbital requirements rather than ask what range of requirements are available because the launch services industry is geared toward satisfying mission requirements. One strategy to identify a launch opportunity is to find a way to use a common orbit (such as Sun-synchronous orbit), or to use propulsion (onboard or on a transfer vehicle) to get from the common orbit to the required orbit. It would be helpful if projects did not have to plan and design for the worst case to avoid over-designing and over-testing. For example, designing for the worst-case eclipse duration for a range of launch opportunities or variations of the same opportunity creates a lot of constraints. Also, it is important to understand where to put the ground assets.
D2-A4.3	**Challenge or Lesson Learned:**	**Future launch opportunities may be impacted when the International Space Station Program concludes.**
	Rationale:	The ISS program has provided a successful platform for CubeSat launches and alternate launch opportunities will be needed once the program concludes.
	Suggestions or additional comments:	– NASA LSP is working to ensure access to space continues after the ISS Program ends. They are fostering and utilizing the growing venture class and rideshare launch services industry through contracts such as Venture Class Launch Services (VCLS), VCLS Demo 2, and Venture-Class Acquisition of Dedicated and Rideshare (VADR). After ISS ends, commercial platforms may be available to deploy from LEO. For CubeSats, rideshare opportunities (including rideshare with transfer vehicles) will probably continue to be the primary path to space.

4.5 Mission Documentation (Day 2, Session B1)

Session overview:
Mission documentation is an integral part of any mission. It helps maintain consistency and provides guidance during development, while also serving as a method to archive information for future use. The most crucial document is the Project Plan—also called the Project Implementation Plan or Mission Implementation Plan. This document establishes how the team operates and serves as an agreement between the project and the main stakeholders. It may also include necessary elements from the Systems Engineering Master Plan (SEMP) to eliminate the need for the SEMP and reduce documentation.

Interface Control Documents are also key to understand what is expected from each side of an interface. Session participants reported issues with SmallSat vendor ICDs, including discrepancies between the documentation provided and the hardware delivered. Inconsistency in vendor products was also observed between the products ordered and the products received since vendors may upgrade/update their offerings without consulting with their customers. These upgrades or updates may cause interface and performance issues that are not discovered until the hardware is delivered.

The quantity of documentation created by a single mission varies by project and organization. In general, projects should strive to maintain a good balance between capturing the right information and reducing documentation overhead. Documentation for documentation's sake can be a burden and detracts value from a mission. Useful and concise documentation helps guide the team, especially when staffing changes occur.

Session notes organized by challenges and lessons learned:

D2-B1.1	**Challenge or <u>Lesson Learned</u>:**	**The project plan is the critical piece of documentation in a mission.**
	Rationale:	The project plan establishes how the team is going to operate.
	Suggestions or additional comments:	– A project plan can be developed in different ways. A standalone document is typical. Some projects have broken down the project plan into a series of PowerPoint slides to reduce the effort required to develop prose, but still relay all the relevant information. It is important to capture the design in the project plan and to make sure that all members of the project are aware of the latest version of the plan. Reaching an agreement on what the team wants to do (at a high level) and then documenting those choices in the project plan is beneficial. Lower-level processes are then captured separately. The project plan should explain how the team is managing systems engineering. From the program office perspective, the project plan is critical.
D2- B1.2	**<u>Challenge</u> or Lesson Learned:**	**Some SmallSat vendors do not understand configuration and interface control or implement those processes poorly.**
	Rationale:	Users have experienced multiple discrepancies between vendor-provided ICDs and actual hardware. Often the hardware that is ordered is different from that delivered because the vendor has incorporated next-generation work or upgrades without notifying the customer.

	Suggestions or additional comments:	– At some point, the interface cannot keep changing and needs to be finalized. To help mitigate this risk, projects should strive to maintain good and constant communication with vendors regarding ICDs and changes to the software/hardware all the way until hardware delivery.
D2- B1.3	**Challenge or Lesson Learned:**	**Defining the quantity of required documentation is a challenge.**
	Rationale:	Determining the right level of documentation requires experience. Requiring too much documentation uses limited resources and does not provide much added value, while too little documentation creates unnecessary programmatic and technical risks.
	Suggestions or additional comments:	– Using the same names for documents in both small and large missions incorrectly drives people to use the same templates blindly, which can consume resources unnecessarily. The more time is spent on filling out every section of a template, the less time is spent thinking about the mission at hand. Templates can be helpful but deleting certain sections should not be viewed as an unacceptable approach. Creating documentation for documentation's sake can be a burden and detracts value from a mission. Multiple documents may contain the same information that is presented differently because the documents are intended for different audiences or stakeholders. Creating these similar products takes valuable team resources.
D2- B1.4	**Challenge or Lesson Learned:**	**Internal documentation is important for the long-term success of a mission.**
	Rationale:	Documentation of critical information ensures the team is working towards a common goal with a common approach throughout the development process.
	Suggestions or additional comments:	– Documentation is important when a team experiences staff turnover. It can help guide new team members and can provide insight into why previous decisions were made. It is valuable to be able to review test data to help address problems with aging instruments. Some documents may not be as useful for phases A, B, or C, but they are important for future phases, especially if anomalies are observed during integration, testing, and operations.

4.6 Risk Program (Day 2, Session B2)

Session overview:
This session focused on the risk program in Phases A, B, and C. PIs often struggle to define a reasonable risk approach for CubeSat programs including the processes used to manage and report risk and identify the risks they will be expected to mitigate. Many missions would benefit from a NASA resource to help them with risk management. Some documentation is available to provide SMA guidance, including the Risk-based Prioritization Handbook for Space Flight Projects (300-HDBK-1007) and the Mission Success

Handbook for CubeSat Missions (GSFC-HDBK-8007). GSFC's Risk Assessment Handbook, GSFC-HDBK-8005, can be helpful guidance for performing risk assessments. SmallSat/CubeSat projects can benefit if someone on the team understands how SMA and risk are handled for a large program and can customize those processes for the SmallSat/CubeSat effort.

Session notes organized by challenges and lessons learned:

D2-B2.1	**<u>Challenge</u> or Lesson Learned:**	**PIs often struggle to define a reasonable risk approach for CubeSat programs in terms of the process used to manage and report risk, as well as the risks they will be expected to mitigate.**
	Rationale:	Scaling down processes used on missions that adhere to NPR 7120.5, NASA Space Flight Program and Project Management Requirements, to develop a risk process to use on missions that adhere to NPR 7120.8 is not a linear or clear-cut effort, which creates challenges for PIs regarding how to best develop an appropriate risk approach for small satellites.
	Suggestions or additional comments:	– Limited budget and staffing resources also contribute to this challenge. A project-level team member who has been through the risk management process and can walk the team through the basics of risk management is helpful. Answering questions like, "What is the risk?" and "What are you going to do about it?" will help guide this process. It would be beneficial to have a NASA resource to assist projects to track risks and ensure the risk tracking process is effective (e.g., context for risks exists and how to best use risk management methodologies). The Small Spacecraft Technology Program (SSTP) plan will be a valuable resource that defines how projects are run (global, center, contractor, etc.) and has been critical in defining how things are done within SSTP.
D2- B2.2	**Challenge or <u>Lesson Learned</u>:**	**Various high-priority SMA practices exist to help reduce risk.**
	Rationale:	Due to the exponential effect that increased risk has on mission cost, leveraging suggested SMA practices will help mitigate potential risks in this area.

	Suggestions or additional comments:	– It is important to know the technical readiness of your partners and supply chain as early as possible to inform both the approach and resource decisions. A forum to enable PIs to interact with one another and ask questions about risk is important. Leveraging some of the available documents on the Small Spacecraft Systems Virtual Institute (S3VI) website may also be beneficial, including 300-HDBK-1007 and GSFC-HDBK-8007. On the parts side, the biggest risk is when parts are misused, not necessarily when they are purchased as COTS products from authorized distributors. Many CubeSat programs cannot afford (time or money associated with) the "high-reliability" version of commercial parts and thus are stuck with the lowest-cost part available for the job. The risks on a highly constrained project are generally those due to: o inadequate testing relative to the launch and operational environment, o unresolved problems at the time of launch, or o items that a mission is essentially stuck with because other options for a critical function either do not exist or cannot be used because they involve too much cost or cannot be accommodated within the project schedule.
D2- B2.3	**Challenge or <u>Lesson Learned</u>:**	**SmallSat/CubeSat program success can be enabled by a team member who understands the concept of SMA/risk and what is typically done for a large program and who can customize the concepts for a SmallSat/CubeSat program.**
	Rationale:	It is unlikely that SmallSat/CubeSat programs can afford to have a full-time person staffed for SMA. A team whose members possess varying areas of expertise and can work together to contribute to risk mitigation will enable mission success. The mindset of each team member is critical.
	Suggestions or additional comments:	– In general, SMA personnel need to understand that 7120.8 missions differ from 7120.5 missions. They need to be able to adapt processes to fit the smaller program and understand the appropriate approach for the mission. Employing a substantive and balanced view of risk will be more effective than focusing on enforcing requirements. It is beneficial to ensure all team members are cognizant of and responsible for risk management. Each team member is an expert on their own subsystem, and all should be able to contribute to the solutions. Teams may want to employ a few key people to serve at the program level and be "go-to" resources for SMA and risk management.
D2- B2.4	**Challenge or <u>Lesson Learned</u>:**	**There are various additional risk mitigation strategies that should be employed in SmallSat/CubeSat programs.**
	Rationale:	Risk is inevitable within SmallSat/CubeSat missions, but resources and best practices exist to help mitigate.

	Suggestions or additional comments:	– The fly/learn/re-fly strategy is good, but missions are getting more expensive. Re-flying can be a problem with the more expensive CubeSat missions. Effort should be put into testing software failures. It's important for a SmallSat program to start testing hardware early. The Risk-based Prioritization Handbook for Space Flight Projects (300-HDBK-1007) is a good resource for highly constrained projects. Informal, peer reviews are another helpful strategy. Employing a bit of extra rigor when characterizing and dispositioning risks may provide a sound basis for relaxing requirements. I.e., projects should make sure there is clear existing context for a risk (rather than "this might happen and thus it is a risk") that can help establish a reasonable estimate of likelihood and consequence and identify paths for mitigation.

4.7 Analysis/Simulation vs. Testing (Day 2, Session B3)

Session overview:
The focus of this session regarded the contrasting uses of modeling and simulation vs. testing during the development stage of a small satellite system. There is a need for early testing at the component or subsystem level. Discussion participants noted that experience from previous projects indicates that running simple tests early at the component level can reveal performance issues that would have significantly impacted projects if the testing had been done later at the system level during assembly.

Projects have experienced negative changes in the quality and performance of COTS components and subsystems sourced from previously successful suppliers. Investigations into the changes have revealed staff turnover and the loss of key personnel as factors driving diminished product quality. The flight heritage of components is an important factor to consider when characterizing the risk of using such components, but equally important is an understanding of how the current component has changed compared to the previous versions flown (including whether key staff have changed), along with the failure and anomaly history.

Typically, SmallSat projects cannot afford to conduct all the analyses or testing desired. Regardless, it is recommended that projects find the time and budget to execute key risk mitigations. Following this approach will save small projects precious budget and schedule later in the project lifecycle when there are fewer resources available to solve problems.

An overriding theme of this discussion was the need to infuse a risk-based mindset with open and clear communication practices to proactively address potential problems. Openly sharing potential pitfalls among project team members makes it much more likely that the team will catch and address issues early, while the impact on resources is still relatively small.

Session notes organized by challenges and lessons learned:

D2-B3.1	**Challenge or Lesson Learned:**	**SmallSat projects can benefit from testing at the early stage of development.**
	Rationale:	Projects need to weed out issues by testing early (subsystem level / engineering development unit/flat-sat). Waiting until later to test can increase the risk of expensive and time-consuming debugging or redesign of the flight system.
	Suggestions or additional comments:	– Testing early reduces overall project cost. Elaborate models and simulations should be test-verified using a simple setup. Challenge the project team to test critical components early.
D2-B3.2	**Challenge or Lesson Learned:**	**Testing on multiple identical systems can be reduced to workmanship checks for subsequent units, and mechanical and electrical interfaces should be carefully checked.**
	Rationale:	Investing in thorough testing of the first unit in a series production will reduce risk on subsequent units. Units delivered later can be tested for workmanship and key interfaces only, saving the project time and cost.
	Suggestions or additional comments:	– In general, you can’t test the attitude determination and control system (ADCS) as a system on the ground. Typically, ADCS components are tested individually to verify modeling assumptions. For SmallSat constellations, consider risk vs. reward when tailoring the test program for system series production and consider modifying tests based on findings from earlier builds.
D2-B3.3	**Challenge or Lesson Learned:**	**Projects need to weigh the risk of not testing components when very little insight into the company’s operations is available.**
	Rationale:	Projects have been experiencing issues with companies that produce components, printed circuit boards (PCBs) and other small spacecraft subsystems. Flight heritage cannot always be assumed to guarantee acceptable quality or performance. Turnover of key people can affect the quality of a company’s product.
	Suggestions or additional comments:	– Buying down risk early by testing components can result in smoother qualification and acceptance later. Changes in components and processes to make or test components happens, so do not assume a component will work just because it did last time. Take extra effort to understand how the product may have changed since last used, including changes in key personnel involved in manufacturing. Consider whether skipping a test is a risk worth taking. In many cases, models and simulations may be the only practical way to test, especially for complex systems.
D2-B3.4	**Challenge or Lesson Learned:**	**Projects need to find the time and budget to mitigate key performance risks.**

	Rationale:	As most SmallSat projects execute quickly with lean staffing and budgets, projects may convince themselves they do not have the time or funding to buy down risk early via testing. Experience shows this practice can lead to much higher costs and hits to schedule later when are fewer resources available to fix problems.
	Suggestions or additional comments:	– COTS component performance should be considered "guilty until proven innocent" via a quick/cheap test of key function(s) under the worst-case operational conditions. In this case, "COTS components" refers to spacecraft subsystem components (not COTS electrical, electronic, and electro-mechanical [EEE] parts, especially those produced at high volume and those in the high-reliability or automotive categories). Reliability is driven by volume, so many COTS small spacecraft components have a long way to go to establish such reliability, due to the natural changes in technology that occur. As project teams develop requirements, they need to consider how to verify and incorporate that information into the Verification and Validation matrix.

4.8 Licensing Process and Encryption (Day 2, Session B4)

Session overview:
This session is focused on the communication licensing process and encryption. Projects must first understand their data and orbital requirements to before beginning the iterative process to define downlink requirements, determine frequency allocation, select ground stations, and select radios. This process must occur as soon as possible to allow time for any surprises during the licensing process. Projects should strive to submit a complete license application to avoid potential delays.

Clarification was obtained for the use of FCC and National Telecommunications and Information Administration (NTIA). In general, NTIA may be used if the government retains effective control over the spacecraft. At the same time, the approval may be affected in the case of commercial use of the spacecraft or commercial use of mission data.

In terms of encryption, NASA has issued a document on command link protection (NASA-STD-1006). Uplink encryption or authentication is required for Class-C missions and below (including Class-D, 7120.8 and Do No Harm).

Session notes organized by challenges and lessons learned:

D2-B4.1	**Challenge or <u>Lesson Learned</u>:**	**Initial steps for a mission before licensing involve an iterative process encompassing data downlink requirements, frequency selection, ground station selection and radio selection.**
	Rationale:	The mission first needs to assess data downlink requirements. These requirements and orbital information will feed into selection of radio(s), frequencies, and ground stations. The radio, frequencies, and ground station options may then affect ConOps and possible limits in data production.

	Suggestions or additional comments:	– Frequency selection is sometimes overlooked and there are numerous rules as to what frequencies are permitted so frequency information must be known prior to purchasing a radio. Frequency allocation also depends on whether the mission is classified as amateur, government, or non-government. Many university-led missions can be classified as amateur, but the Federal Communications Commission (FCC) is carefully evaluating if these missions should be qualified as amateur. Additionally, certain frequency bands are allocated for government use only, non-government use, or combined use. The frequencies need to be specified when developing the requirements of a mission.
D2-B4.2	**Challenge or Lesson Learned:**	**Apply for licensing as soon as the project knows the requirements and system design is mature with a complete application.**
	Rationale:	The more time a project has to obtain licensing the better, but projects should not sacrifice timing for accuracy of information. Wrong or incomplete data can delay the application. The FCC tends to have stricter orbital debris thresholds when compared to the NTIA, so project should allow enough time to react if a component does not meet the requirements.
	Suggestions or additional comments:	– The rule of thumb is: "know what you need, seek out help from the spectrum community, and make sure you prepare all the required information before applying".
D2-B4.3	**Challenge or Lesson Learned:**	**Missions may obtain licensing approval using the National Telecommunications and Information Administration (NTIA) instead of the FCC depending on who has true effective control of the spacecraft and the commercial use of a specific mission.**
	Rationale:	Effective control refers to dictating when and how a spacecraft operates. Effective control can be achieved when a government organization operates the spacecraft, or an entity like NASA can retain effective control by dictating via contract how a grantee or contractor operates the spacecraft. Another aspect affecting the use of NTIA is the commercial use of the spacecraft. Selling data produced by the spacecraft or providing any type of commercial service may preclude the usage of NTIA for licensing.
	Suggestions or additional comments:	– For instance, if there is some issue with interference, NASA could tell the contractor to turn off. So, if you retain effective control, then you would work with the FCC. – Typically, the missions going through NTIA are the ones coming out of NASA centers. Missions from academia and industry typically use FCC. In some cases, such as the Solar Dynamics Observatory (SDO) and Lower Atmosphere/Ionosphere Coupling Experiment (LAICE), have spacecraft that are primarily university run, but NASA retains the effective control and are going through NTIA. The FCC and NTIA coordinate on spectrum approval and FCC provides final approval of the orbital debris analysis.

D2-B4.4	**Challenge or Lesson Learned:**	**Uplink encryption or authentication is required for Class-C missions and below (including Class-D missions, missions adhering to NPR 7120.8, and Do No Harm missions).**
	Rationale:	NASA has issued the Space System Protection Standard (NASA-STD-1006) for command link protection. The goal is to ensure all future spacecraft have protected command links.
	Suggestions or additional comments:	– NASA Class 3 missions (Class C and D) can authenticate without encryption if there is no propulsion on the system. In that case, missions should employ proactive authentication that shows that the received command comes from an authorized source like a command center. (Note: per NASA-STD-1006, Category 3/Class C or Class D missions may authenticate without encryption if they have no propulsion. This provision includes missions below Class D)

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5. Phase D System Assembly, Integration and Test, Launch (Day 3)

Phase D sessions targeted activities and lessons learned during system assembly, integration and test (I&T), and launch and focused on the following topics: project management, systems engineering, the integration and test plan, day-in-the-life testing, ground systems, and data processing systems.

Overall, Phase D can be a challenging and stressful time for the mission development team. Even significant schedule and cost reserves can diminish if an intractable technical issue is encountered. During Phase D, the team often works long hours to complete integration and environmental testing and resolve issues that arise. Work undertaken in advance by the project manager (PM), systems engineer (SE), and technical leads can lay the groundwork to mitigate issues.

The PM must manage schedule, budget, risk, and personnel resources to tackle the "unknown unknowns" during Phase D. SmallSats often have strict delivery timelines, and the PM should strive to mitigate team members' fatigue and maintain morale—including pitching in to fill technical roles as needed. When planning the schedule, the PM should budget adequate time for testing (e.g., double the expected time) to allow for inevitable delays.

Systems engineering challenges frequently concern management and communication of risks among various mission stakeholders. The SE team should fully understand the top-level requirements to inform descopes. It is also important to test interfaces as early and as often as possible since documentation and models are not always accurate. Sufficient time should be allocated for system-level testing to enable the team to react to issues and determine appropriate penalty testing.

Integration and Test (I&T) planning for SmallSat missions managed according to NPR 7120.5 differs from that for missions adhering to NPR 7120.8, "Do-No-Harm" projects, or Institutional-Best-Practices projects, especially with respect to the level of documentation, rigor of testing, descope options, workforce planning, and type of test facilities employed. Test teams for the 7120.8-governed missions tend to be smaller and team members may perform multiple roles including quality assurance; therefore, it is useful to involve experienced personnel who can make calculated decisions based on risk posture. NASA could benefit greatly from standardizing processes for Class D missions such as SmallSats, since different institutions tend to follow their own practices and the level of tailoring is not consistent.

Testing conditions should be as flight-like as possible (even for subsystem-only tests) and thermal vacuum (TVAC) testing should be conducted using as much of the full system as possible. All housekeeping data should be collected during testing to capture as much information as possible. Care should be taken to test the extreme cases to ensure the system is fully understood, that fail-safe modes trigger, and the system operates as expected during these conditions. In addition, testing of non-flight conditions—for example, the conditions encountered during delivery to the launch provider or the effects of storage on the system—can be valuable.

Session participants agreed that the Ground System (GS) encompasses hardware, software, processes, and very early planning and testing and that three major GS capabilities are required to support SmallSat missions: the Baseband (BB) system, the Radio Frequency (RF) system, and the Command and Control (CC) system. Effective Phase D ground system testing requires adequate equipment, knowledge, and resources to replicate the operational environment. Government, commercial, and academic organizations all provide GS capabilities and services, but these services are diverse, awareness of such services is limited (which can impact mission planning), and the services are sometimes challenging to learn about and implement.

Session participants discussed the type and cadence of housekeeping data that should be collected during this phase, how to determine whether data processing should occur onboard or on the ground, and the different best practices regarding data products for science missions vs. technical demonstrations. If the mission's data downlink is limited, it is useful to include as much summary data in bit-flags as possible. It is also beneficial to maximize the amount of data recorded during ground testing; in the event an on-orbit anomaly occurs, this ground test data will assist in debugging. It is vital to develop a data interface control document (ICD) and communicate spacecraft power/processing constraints to the science/instrument team to establish common expectations. It is also important to establish how NASA and the payload (which could be run by an academic or commercial partner) exchange data to ascertain if there is a need to control the type of data that can be shared.

5.1 Project Management (Day 3, Session A1)

Session overview:
This session focused on project management during Phase D—particularly on the many roles the Project Manager must play during this phase. It is of utmost importance to keep the work flowing smoothly; therefore, the PM must ensure that personnel have access to resources, tools, facilities, and parts necessary to perform testing and integration within the allotted schedule.

The PM must also ensure transparent and open team communication. Effective tools to facilitate inter-team scheduling and communications are vital to the success of the I&T campaign. Generally, on SmallSat missions, the same team members work on the project from Phase A to the end of I&T. All team members perform multiple tasks, so everyone needs to be a team player. Team members must communicate effectively and be aware of technical details concerning the complexities of building and integrating the system, especially during handoffs between shifts. The PM needs to ensure team members are mentally prepared (e.g., for long shifts) and understand what to expect if they have not conducted I&T before.

The PM of a small team might need to obtain additional outside support to ensure personnel with a range of experience are available to deal with unknown issues. Sometimes there is a perception that SmallSat mission teams can be composed of many early-career members. While it is true that early-career employees can benefit from being on a SmallSat team, the team must include enough knowledgeable key team members who can either resolve issues themselves or know personnel who could do so.

The PM must vigilantly monitor external factors that can affect the I&T schedule. Oftentimes larger projects take precedence over SmallSat projects, which can add serious risk to the SmallSat mission. SmallSat PMs should identify other facilities nearby (e.g., a vibration test table) that the team could use for testing in case the equipment required for SmallSat testing is being utilized by another project.

Above all, during the I&T campaign, the PM must be aware of team dynamics and the level of exhaustion and fatigue in the team. PMs should boost morale and lead by example, for instance by volunteering for graveyard shifts during TVAC testing or dropping in during weekends during testing to bring refreshments and food.

The importance of certain key tests cannot be over-emphasized. PMs should ensure adequate tests are performed including end-to-end over-the-air testing for communications, thermal vacuum testing, fault testing, and testing of corner cases. Proper documentation will serve to provide history and context, especially if issues need to be debugged later on orbit.

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Session notes organized by challenges and lessons learned:

D3-A1.1	**Challenge or <u>Lesson Learned</u>:**	**Project Managers must expect to play numerous important roles during Phase D I&T.**
	Rationale:	Leading a team through I&T requires a Project Manager to wear multiple hats and ensure that the team is fully supported through a demanding schedule.
	Suggestions or additional comments:	– The PM manages the budget and keeps things moving during I&T, making sure there are enough procurement funds to purchase any items that were overlooked (e.g., cables or different facilities). – The PM needs to ensure that personnel have the resources they need. Proper tools to enable communication among team member are very important. Everyone on the team needs to know what they need to do and when they need to do it. – The PM must be able to make quick decisions when things change or unforeseen challenges occur. The PM also needs to understand the risk posture of the mission. When something bad happens, the PM must decide which risks to accept and which to mitigate. – PMs also need to develop detailed I&T schedules since this effort is very fast paced.
D3-A1.2	**Challenge or <u>Lesson Learned</u>:**	**PMs play a large role in supporting team personnel in various ways throughout I&T.**
	Rationale:	I&T is a particularly grueling time involving fast paced schedules and long days.
	Suggestions or additional comments:	– The PM needs to be sure that work is shared among team members and that individuals do not become burned out. – The PM must know the team members and their roles well enough to recognize when someone is fatigued. Sometimes the PM must send someone home because they are fatigued and could possibly make a mistake. The PM must also lead by example, e.g., taking graveyard shifts or a 10-hour shift if there is a lack of personnel. – PMs are also instrumental in supporting team morale. It means a lot to have the PM show up during a shift to provide support and positive feedback and bring coffee or snacks. The PM should assist when people are struggling or need relief. – It is useful for the PM to call in people from outside the project with relevant experience or who want to get experience with a task (e.g., TVAC test) to sit in on shifts.
D3-A1.3	**Challenge or <u>Lesson Learned</u>:**	**At times, the role of the PM might need to be expanded to fully support the team through I&T.**
	Rationale:	The PM needs to ensure the team has the necessary support and resources to do the job.

	Suggestions or additional comments:	– PMs should be multifunctional, so they are able to take on some of the team roles (e.g., technician). PMs should step in when the team needs help or support or to fill a role when there is a weakness or deficiency. – It is very helpful for the PM to take a hands-on approach and step in when the team needs to take a break (e.g., the PM could run an easy test). – PMs should also admit when they do not know something, but should know who to ask to obtain the necessary information.
D3-A1.4	**Challenge or <u>Lesson Learned</u>:**	**PMs need to ensure that their team is prepared for what to expect during I&T and that they are set up well to succeed, particularly regarding matters related to staffing during testing.**
	Rationale:	I&T requires that an entire team put in long, grueling hours. It requires intentional staff selection and managing scheduling expectations for the team to succeed during this phase.
	Suggestions or additional comments:	– The PM needs to ensure the team has sufficient resources and that team members are mentally prepared (e.g., for long shifts) and understand what to expect if they have not conducted I&T before. PMs of small teams might need to obtain external support to supplement team expertise (e.g., someone with Guidance, Navigation, and Control [GNC] experience for an attitude control test). – Scheduling is very important. PMs should be sure there is sufficient staffing to cover shifts, so team members do not become fatigued. Each shift should last less than 12 hours. – It is crucial that the PM chooses the right staff for I&T. The PM should prioritize positive team dynamics and culture when selecting team members. All team members need to pull their weight or there could be discord. Team members need to understand the details of the I&T scope. Those who are less experienced must be willing to learn whatever is necessary. – Generally, on SmallSat missions, the same team members work on the project from Phase A to the end of I&T. All team members perform multiple tasks, so everyone needs to be a team player.
D3-A1.5	**Challenge or <u>Lesson Learned</u>:**	**PMs must anticipate risk within I&T schedules and plan to adequately mitigate.**
	Rationale:	Anticipation and mitigation of risks may help avoid the need for the project to return to the I&T facility, which is very common for SmallSat I&T.

	Suggestions or additional comments:	– It is a best practice to for PMs to include a healthy margin in the schedule for preparation for entry into the test facility. – Many SmallSat mission schedules become compressed near the launch date, making it impossible to add extra margin. Since SmallSat teams are generally small, it is usually not possible to implement 7-day work weeks or add extra shifts unless more people can be brought in to help. It is important for the PM to develop relationships with other projects that might be able to help with additional shifts. – Develop communication between other project teams that could help out in a bind. For example, during testing, a project might unexpectedly need cables that would take a long time to procure. Risk could be removed if another project could lend the cables. – Make sure the team has a range of experience to deal with unknown issues. Sometimes there is a perception that SmallSat missions can be composed of many early career members. While it is true that early career employees can benefit from being on a SmallSat team, the team must include enough knowledgeable key team members who can either resolve issues themselves or know personnel who could do so. – Oftentimes larger projects take precedence over SmallSat projects, which can add serious risk to the SmallSat mission. The PM should identify other facilities nearby (e.g., a vibration test table) that the team could use for testing in case the equipment required for SmallSat testing is being utilized by another project. One NASA center is advocating to get its own dedicated test facility, such as a TVAC chamber, to address the lack of access to test facilities for SmallSats.
D3-A1.6	**Challenge or <u>Lesson Learned</u>:**	**Often it takes only three days from delivery of a SmallSat to launch, but if there is a launch delay, it is generally straightforward to maintain the spacecraft.**
	Rationale:	Sometimes a SmallSat is not launched or deployed for a long time (e.g., as much as three years). One of the most common issues related to long-term storage is the need to charge the battery.
	Suggestions or additional comments:	– The battery could be charged or swapped out with a charged battery. – Design and test the battery system so it can withstand a longer storage life (e.g., 6-12 months) and design the SmallSat/CubeSat such that it is possible to charge the battery after launch delivery. It is important to understand the risk posture if it will not be possible to access to the spacecraft to charge the battery.
D3-A1.7	**Challenge or <u>Lesson Learned</u>:**	**It is inevitable that resource limitations will restrict some aspects of testing (e.g., fault management) during I&T, but certain tests should not be omitted.**
	Rationale:	

	Suggestions or additional comments:	– Do not skimp on TVAC; at a minimum test at least one cold and one hot cycle. – It is very important to perform end-to-end communication tests over the air. – Document all aspects of testing as much as possible. Document results from all functional tests over time, including when the test was performed and any differences between the various tests performed. If an issue is observed on orbit, the documentation can serve as a reference to assist in determining what happened or how to resolve the issue. – Understand what the critical components in the telemetry will be. Always anticipate issues that will need to be debugged on orbit.

5.2 Systems Engineering (Day 3, Session A2)

Session overview:
This session focused on the systems engineering challenges and best practices during Phase D: System Assembly, Integration and Test. A significant portion of the discussion was focused on determining the right level of testing and risk acceptance for Class D missions. Specifically, the discussion centered around how to ensure that risk is adequately communicated within the team, to the managing organization, to the sponsor, and to the reviewers. Often, there are disconnects that need to be resolved. Specifically, there is a tendency to skew to "low" risk and require more testing, redundancy, etc. than necessary. These issues varied in severity depending on the organizations.

With regards to testing, session participants discussed the advantage of testing early in SmallSat programs to uncover issues and allow enough time to implement necessary solutions. It is often the case with SmallSat missions that a lot of testing is done later in the program, which does not leave sufficient time to fix any identified issues. Though SmallSats typically have less budget to do extensive system-level testing before integration, they have more of an opportunity to do integrated testing for a longer period at the end of I&T because of their small size, which is an advantage.

A large portion of the session discussion focused on risk posture of Class D missions. The level of testing needed e depends on the mission and will likely vary for science missions, technology demonstrations, and constellation missions. Participants also noted that determining the optimal level of testing for each mission is an ongoing challenge for SmallSats and can vary according to the experience of each mission team. Some teams will require less testing and have a higher acceptance of risk than others. It was also noted that team members who are accustomed to working with larger missions have more difficulty understanding how testing needs to be tailored to accommodate the lower risk posture of Class D missions. The amount and type of testing SmallSats undergo depends on the risk posture assumed, which often comes down to a judgement call with some determined constraints. Having experienced team members is valuable, as they can make these judgement calls based on extensive experience. It was also noted that NASA provides guidance regarding what risk can be accepted with SmallSat missions.

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Session notes organized by challenges and lessons learned:

D3-A2.1	**Challenge or <u>Lesson Learned</u>:**	**Perform system-level testing with sufficient time to react to issues and determine appropriate penalty testing.**
	Rationale:	Given the SmallSat risk profile, it is common for testing to be deferred to a later stage where the satellite is more integrated, but tests should only be deferred if there is sufficient schedule slack to react to any issues that are uncovered during testing.
	Suggestions or additional comments:	– Penalty testing is highly recommended to reduce the risk of new problems that result from any rework or corrective actions. – To appropriately size the penalty testing, projects should clearly understand how risks depend on the level of de-integration required.
D3-A2.2	**Challenge or <u>Lesson Learned</u>:**	**Test interfaces as early and often as possible, as documentation and models are not always correct.**
	Rationale:	Subsystem testing does not often uncover issues with interfaces and mechanical stack-ups that exist at the system level.
	Suggestions or additional comments:	– Where possible, coupling system testing with certain subsystem testing at the early stages will help decrease risk if testing after full integration is not possible. – It is not uncommon for documentation and models to contain errors and it is the project's responsibility to verify the actual systems.
D3-A2.3	**Challenge or <u>Lesson Learned</u>:**	**Proper understanding of the top-level requirements will inform descopes.**
	Rationale:	At this stage of the integration, there may be insufficient time to deal with issues that arise, and difficult decisions must be made to maintain the mission integrity if descopes are considered.
	Suggestions or additional comments:	– Ensure that the stakeholders are in the room when potential descopes are discussed. – Lower-level requirements can often be sacrificed if higher-level crucial requirements are preserved.
D3-A2.4	**Challenge or <u>Lesson Learned</u>:**	**As opposed to traditional flagship class missions, CubeSats are unique in that the entire system is small enough to be fully tested. Projects should leverage this feature in testing campaigns.**
	Rationale:	Unique tests can be performed on a CubeSat flight system and, in some cases, such tests provide higher confidence in the mission products.
	Suggestions or additional comments:	– Identify any mission-unique elements that can be performed on the small satellite due to its form factor.

D3-A2.5	**Challenge or <u>Lesson Learned</u>:**	**Do not skimp on the telemetry gathered during the testing campaign, and, where possible, in flight.**
	Rationale:	Telemetry data can help discern issues and often can be used to inform on-orbit performance as well.
	Suggestions or additional comments:	– Plan ahead for telemetry required during testing to ensure that all useful data is collected. – Test products should be maintained and used throughout the testing campaign.

5.3 Integration and Test Plan (Day 3, Session A3)

Session overview

This session focused specifically on the integration and test planning during Phase D for missions adhering to NPR 7120.8 versus those governed by NPR 7120.5. Topics discussed in this session included: the level of documentation, descope options, types of facilities used during testing, workforce planning, mishap reporting, and the rigor of testing required for both types of missions. The information recorded in this chapter can benefit both 7120.5 and 7120.8 missions seeking to develop and implement a test plan to verify compliance with launch vehicle environments or conducting workforce planning and risk assessment.

Session participants agreed that a significant amount of tailoring is allowed for Class D and sub-class D missions. Missions adhering to 7120.8 are allowed greater flexibility to tailor testing regimens than 7120.5 missions.

Many project managers of 7120.8 missions try to descope tests that are not specifically required (e.g., Electromagnetic Interference [EMI]/Electromagnetic Compatibility [EMC] testing). This practice is normally acceptable for 7120.8 missions, given their higher risk posture and mission classification. However, some tests (e.g., TVAC testing and vibration testing) should always be performed.

All participants agreed that regardless of whether a mission adheres to NPR 7120.8 or NPR 7120.5, the launch vehicle ultimately determines the type of testing required. Unfortunately, during the early stages of launch vehicle development, all required environments are not clearly defined. Early on, many projects are thus forced to test to General Environmental Verification Standards (GEVS), which may or may not be conservative depending on the launch vehicle. Fortunately, as the launch vehicle gets further along in its development, many of the environments are defined further. GSFC-HDBK-8007 includes a CubeSat version of GEVS that is less conservative than the full GEVS document.

Documentation requirements for testing vary greatly between 7120.8 and 7120.5 projects. Testing documentation for 7120.8 missions often consists of a simple PowerPoint presentation or Visio or Cad drawing. Missions adhering to NPR 7120.5 require more detailed documentation and approval before testing. Documentation is key to capture processes and lessons learned. All missions should model best practices such that in the event of an anomaly, testing documentation is readily available to facilitate quality assurance, lessons learned, and efforts to determine root cause. Session participants also noted that the various NASA centers use different systems and processes to report anomalies for 7120.5 and 7120.8 missions.

Another difference between 7120.8 and 7120.5 missions is the level of staffing employed. Teams working on 7120.5 missions are typically at least 3-4 times larger than those working on 7120.8 missions.

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For 7120.8 missions, tests are generally descoped to reflect the smaller team, team members assume many different responsibilities, and risk posture is high. On a 7120.8 mission, for instance, it is not uncommon for the mechanical engineer to also serve as the electrical lead for the mission. In fact, the testing philosophy, anomaly reporting, and documentation decisions on 7120.8 missions are often driven by workforce planning decisions made at the genesis of the mission.

In conclusion, different organizations apply different staffing and tailoring requirements for Class D and sub-class D missions, and the level of tailoring employed by each institution is not clearly understood. NASA may want to explore whether standardizing this subset of missions could yield benefits. In addition, participants noted that testing facilities and capabilities also vary at each NASA center, possibly limiting the types of missions and projects each center can support.

Session notes organized by challenges and lessons learned:

D3-A3.1	**Challenge or Lesson Learned:**	**Launch vehicle environments are not clearly defined during the early phases of launch vehicle development; consequently, many projects must rely on GEVS for their test environments.**
	Rationale:	
	Suggestions or additional comments:	– GEVS provide a conservative baseline for spacecraft development. Following and/or tailoring the GEVS standards outlined in GSFC-STD-7000A will provide confidence for mission success until updated environments are provided by the launch vehicle provider. The Appendix of GSFC-HDBK-8007 includes a CubeSat version of GEVS with moderately less conservatism.
D3-A3.2	**Challenge or Lesson Learned:**	**All 7120.8 and 7120.5 missions generally tend to descope EMI/EMC testing and typically perform self-compatibility testing.**
	Rationale:	Unless specified by the launch provider, this test tends to be a self-compatibility test between the payload and spacecraft avionics.
	Suggestions or additional comments:	– This approach tends to work for most technology demonstration missions, and performing this test early in the mission with high-fidelity prototypes allows missions to identify issues early and fix problems before they impact mission success. – Missions should determine which EMI tests outside of self-compatibility are most relevant to that particular launch and operational environment. – Although 7120.8 missions have greater flexibility in this arena to descope, there are instances where even 7120.5 missions can descope EMI/EMC testing.
D3-A3.3	**Challenge or Lesson Learned:**	**Other tests can be frequently descoped or eliminated for 7120.8 missions. Each proposed test is weighted according to a specific launch vehicle requirement to determine whether the test is needed.**
	Rationale:	Schedule and budgetary constraints for 7120.8 missions contribute to additional descoped testing.

	Suggestions or additional comments:	– Other tests that are typically descoped or eliminated for 7120.8 missions are shock testing, sine burst testing, and acoustics testing. However, 7120.8 missions do try to accommodate TVAC testing as well as vibration testing. – Both 7120.5 and 7120.8 missions conduct some 3-axis sine or random vibration testing during the development phase. This testing is then supplemented with a pre- and post-signature sweep after testing and, at times, a functional test to ensure that the unit is still operational after testing.
D3-A3.4	**<u>Challenge</u> or Lesson Learned:**	**In most organizations, each SmallSat mission team member wears multiple hats and fulfills multiple roles**
	Rationale:	SmallSat missions are often cost- and schedule-constrained and cannot support large teams.
	Suggestions or additional comments:	– SmallSat mission teams should include experienced members who can make calculated decisions based on risk posture.
D3-A3.5	**<u>Challenge</u> or Lesson Learned:**	**During I&T, smaller missions generally tend to undergo few inspections and implement less stringent quality assurance (QA) processes. In many facilities, engineers are trained to perform I&T instead of relying on flight technicians.**
	Rationale:	SmallSat missions are often cost constrained and cannot hire a lot of flight technicians or support large teams
	Suggestions or additional comments:	– With appropriate training, engineers can perform the work usually accomplished by larger teams with experienced flight technicians.
D3-A3.6	**Challenge or <u>Lesson Learned:</u>**	**Test plans may be tailored but documentation of flight hardware testing and anomaly reporting are key to all missions—regardless of size**
	Rationale:	Documentation is key for traceability and missions should “test as you fly” (i.e., ensure that tests and simulations accurately reflect the planned mission profile, plus margin)
	Suggestions or additional comments:	– Documentation of assembly and test is very important to maintain traceability; documentation requirements should be the least tailored aspect of the I&T process
D3-A3.7	**<u>Challenge</u> or Lesson Learned:**	**NASA centers use different systems and processes to report anomalies for 7120.5 and 7120.8 missions.**
	Rationale:	

	Suggestions or additional comments:	– Wallops/GSFC, LaRC, and JPL all use different systems to report mission anomalies. o For 7120.8 missions, WFF sometimes uses something as simple and informal as an Excel spreadsheet maintained by the Mission Systems Engineer to report and disposition anomalies, whereas for 7120.5 missions, the Problem Failure Reporting System (PFR) system is used. o LaRC uses an informal anomaly reporting system for 7120.8 missions, however, towards the end of the Shields-1 project, the senior executives at Langley reportedly were interested in all anomalies on the mission and how they were being dispositioned. On subsequent 7120.5 missions, LaRC utilized the NCR anomaly reporting system on Onespace. The NCR system is not too cumbersome, and it enables anomalies to be easily tracked and dispositioned.

5.4 Day-in-the-life Testing (Day 3, Session B1)

Session overview:
Participants in this session discussed aspects related to testing small satellites during Phase D. Topics covered included simulating the real flight environment during testing, what hardware to test, and testing in a flight-like manner. The discussion centered around conducting tests at the subsystem level throughout development. The number of subsystem tests that can be performed is dependent on project budget and timeline. Participants suggested that projects use software that is as flight-like as possible during testing (even for subsystem only tests). Sub-routines should be employed (including dummy loads and extra cabling if needed) to collect all housekeeping data and capture as much information as possible during testing.

Using flight-like scenarios during testing is key for mission success. Before testing, thermal modeling should be used to identify the conditions to examine during TVAC testing. Projects should be sure to test the extreme cases to ensure fail-safe modes trigger and systems continue to operate as expected. To trigger fail-safe modes, sensor output can be simulated by changing parameters through software commands if it is not possible to simulate real sensor output. It may be important to run the TVAC test for multiple days to ensure fail-safe modes are triggered for worst case conditions. An important aspect of flight-like TVAC testing is to exercise the radio and beacons to debug any communications issues. During these flight-like TVAC tests, it could be beneficial if satellite operators test commands and observe telemetry results during extreme conditions to better understand the satellite.

Session participants agreed that testing in non-flight conditions—such as conditions experienced during delivery to the launch service provider—can be just as important as testing in flight conditions. For example, on the Shields project, testing had to be conducted to prove that the satellite would not turn on until deployed as part of the Do No Harm (DNH) requirement. This effort involved testing of the satellite in the deployer. CubeSats to conduct biological experiments can also experience issues before flight; the outgassing of electronics during storage, can affect the microorganisms in the experiment. This potential issue needs to be understood to make sure the experiment results are valid.

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Session notes organized by challenges and lessons learned:

D3-B1.1	**<u>Challenge</u> or Lesson Learned:**	**The full satellite and/or flight software may not be available for TVAC testing.**
	Rationale:	Satellite software and/or some hardware may still be under development.
	Suggestions or additional comments:	– The focus of satellite TVAC testing should be accomplishing radio communications without any ethernet cables (“plugs out”) and testing the systems over the air. Projects should try to operate the satellite using the radio as if it were operating in space to. identify issues that would have otherwise remained unseen. – Test as much hardware during TVAC testing as possible. – Make sure to test functionality. – Ensure to include radios in the testing environment if the test is to represent the full satellite. – Recognize that TVAC testing not only provides a good emulation of the on-orbit environment, it also draws out moisture and identifies undesired conductive paths prior to flight. – Day-in-the-life testing (DILT) may vary based on the requirements of a mission’s launch service provider. The Shields mission had a DILT requirement to prove it would not turn on (for DNH). The Shields team also wanted to ensure the project would operate beyond the DNH requirement, so they did their own informal DILT as well.
D3-B1.2	**Challenge or <u>Lesson Learned</u>:**	**Incremental testing of systems is acceptable.**
	Rationale:	Incremental testing enables early testing of components while the project is still under development.
	Suggestions or additional comments:	– Simulate other subsystems connected to the subsystem being tested. – Incremental testing can enable more robust testing of each subsystem. – It can enable the team to track anomalies and gather more subsystem-specific data.
D3-B1.3	**Challenge or <u>Lesson Learned</u>:**	**Various open source or market tools are available to simulate space physics during day-in-the-life testing.**
	Rationale:	These tools enable simulation capabilities when some hardware might not yet be available.

	Suggestions or additional comments:	– Space Environment Information System (SPENVIS) and CREME96 (Cosmic Ray Effects on Microelectronics) are useful tools to help find radiation environment specifications. – A thermal modelling approach can be used to determine the environment a satellite will be operating in. – At Goddard and WFF, teams have been developing software tools to help simulate various pieces of hardware (e.g., NASA Operational Simulator for Small Satellites [NOS3]), which is useful when teams need to simulate without hardware. – Another resource called 42, is an attitude control system (ACS) simulation environment. This resource allows input to be provided to an ACS system or directly to the flight computer to simulate various flight scenarios. – Missions can also try to use common flight and ground software that builds on itself over time; each mission contributes to the course, reduces development times for future missions, and avoids needing to start from scratch.
D3-B1.4	**Challenge or Lesson Learned:**	**Using a "test-as-you-fly" approach is crucial during this phase.**
	Rationale:	A "test-as-you-fly" approach may enable the team to identify issues during flight that otherwise would not have been observed.
	Suggestions or additional comments:	– Make sure to test radios. – Test with as few cables connected as possible to simulate flight. o GNC antennas and shield rooms were cited as good resources. – One participant used AS25 communications, which allowed the team to test the entire signal chain by testing software through the hardware chain and observing the satellite response. Later, the system was taken to the actual ground station to do the same test. – Test with plugs out to understand the range of your battery levels. – Satellite operators should run the tests and send the commands to see the telemetry coming back, especially if the operations team is different from the test team. – One participant mentioned that they try to stimulate as many of the sensors as possible. For many of the triggers and software, missions should consider building in a DILT scenario in the software that can be enabled. This approach is not without risk but enables the ability to change various parameters that may trigger scenarios that might kick the satellite into a failsafe state. This approach also allows for more robust testing in various stages.
D3-B1.5	**Challenge or Lesson Learned:**	**DILT can sometimes be challenging to execute on small projects due to budget limitations. How can missions accomplish this testing if access to the primary is limited?**

	Rationale:	Budget limitations and limited to no access to the primary launch vehicle can inhibit the amount of testing that can be performed on some SmallSat missions. For example, a mission needed to continue testing and run reaction wheels frequently before flight, but had trouble getting access from the primary payload.
	Suggestions or additional comments:	– Obtaining access to the primary payload to access the satellite depends on the agreement with the launch provider. In the case of one session participant, the mission had no chance to do anything except charge the spacecraft prior to launch. – One way to mitigate this issue is to incorporate multiple different hardware options in your design. – The Shields 1 team was concerned about the project's solar panels turning on the CubeSat. The team ended up having to negotiate to get covers installed on the deployers so that the CubeSat did not turn on. o The Shields 1 team had to prove through analysis and testing that the project would be able to survive inside a deployer for up to nine months, because integration was in California, but the launch was in New Zealand. The team was given extra time at integration to ensure the system was fully charged but had no access to the CubeSat once it was delivered for launch.
D3-B1.6	**Challenge or <u>Lesson Learned:</u>**	**Missions should operate the vehicle during testing for at least 24 hours straight to determine if anything needs to be debugged.**
	Rationale:	
	Suggestions or additional comments:	– One participant noted that they operated the system for ten days, not 24 hours. The team needed to ensure the flight computer would reset to prove certain functionalities. This participant noted that testing to make sure the beacon is functioning properly, that it can be turned off and on, and that the data stream is functioning correctly, are three very important factors that DILT should cover.
D3-B1.7	**Challenge or <u>Lesson Learned</u>:**	**Missions can anticipate data parameters that may be needed only in special circumstances and consider enabling download of that data.**
	Rationale:	
	Suggestions or additional comments:	– One team had an issue in flight where the project was consistently kicked out of fine pointing mode. There were many parameters within the ACS system that the project team did not think were needed but it turned out they would have liked to have those parameters downlinked in the housekeeping data to provide more insight into the problem.

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5.5 Ground Systems (Day 3, Session B2)

Session overview:
The Ground Systems (GS) session addressed the importance and criticality of spacecraft development laboratory and GS capabilities to the I&T and flight phases of a SmallSat mission. The SmallSat mission GS is comprised of hardware, software, processes, planning, and testing. In general, the following major elements of the GS were broadly identified as required for end-to-end operational support of a SmallSat mission:

- Baseband (BB) system
- Radio Frequency (RF) system
- Command and Control (CC) system

To meet SmallSat mission GS requirements, the BB system must handle modulation and demodulation functions to transfer SmallSat mission data between the spacecraft and the ground station. The BB system must also be capable of processing and formatting data using standards/protocols that are consistent with the SmallSat mission project development philosophy involving shorter schedules, smaller teams, lower cost, and risk posture considerations.

The RF system consists of the ground antenna(s) and the associated electronics for acquisition, tracking, and modulation/demodulation of SmallSat mission command, telemetry, and mission data links.

The CC elements process formatted data bit streams into appropriate mission operator telemetry health and status, or into formats for commanding the spacecraft for mission display, data transmission, and operational management.

Participants in this session addressed government, commercial, and academic GS expertise and services; the evaluation of GS options; risk mitigation to ensure operational compatibilities; the need for early scheduling of GS test and verification activities; and considerations related to the overall cost of both ground laboratory I&T and GS capabilities.

Additional discussions concerned the increasing options available for BB, RF, and CC elements. The availability and sometimes even a sufficient level of awareness of these options is necessary for planning GS capabilities, but obtaining the required information is an ongoing challenge, especially during the early formulation and proposal phases of SmallSat missions. Participants noted that although the number of GS software tools and their capabilities are increasing and may result in potentially higher payoff, the user learning curve can be very steep. In particular, insufficient knowledge of who to contact, lack of initial training, and poor documentation can be barriers to setting up a robust and functional GS—even with some of the very capable GS government-provided tools. Lastly, participants strongly recommended that NASA convene more SmallSat forums and that more time be allowed for each session.

Session notes organized by challenges and lessons learned:

D3-B2.1	**<u>Challenge</u> or Lesson Learned:**	**There is a wide diversity of GS services and capabilities offered by the government, commercial, and academic providers.**

	Rationale:	Pro: A wide range of GS services capabilities are available from both domestic and international providers. Con: In many cases, providers employ totally different approaches regarding obtaining GS services, pricing, actual vs. advertised support provided, "front-door" capabilities available to new users for obtaining ground services, the user requirements definition process, licensing, and other aspects.
	Suggestions or additional comments:	– Invite all GS providers to provide information about their capabilities using a well-developed standardized template; the template should require a clear description (e.g., a single graphic) depicting the "front door" customer interfaces and processes with timelines compatible with the shorter schedules of small spacecraft. – Create a website of available GS providers that contains **only** the standardized template information. – Sponsor additional international collaborations and forums; develop relationships with worldwide GS providers to build international capability and increase flexibility, especially for missions beyond LEO. – Government and some commercial GS providers are still using a more "traditional" approach for early user customer processes and assessments. There should be a more SmallSat mission "friendly" and appropriate "buy by the yard" GS mission planning approach. – Incorporate a "Test as you Fly" approach early and often to SmallSat mission development activities for I&T, and employ a specific "end-to-end" testing approach when possible.
D3-B2.2	**<u>Challenge</u> or Lesson Learned:**	**The user experiences with both domestic and international commercial GS providers are very diverse.**
	Rationale:	Possibly due to the lack of international commercial standardizations and/or the rapid entry of new GS providers to the market, it is challenging for SmallSat mission teams to keep abreast of the myriad and changing front-door processes and user documentation and integration processes. In particular, with smaller commercial GS providers, documentation upkeep is often challenging for the SmallSat mission team, as these companies are often using state-of-the-art technology that changes quite often. GS provider capabilities may change between the initial SmallSat mission planning and development phases and the final user contract commitment.
	Suggestions or additional comments:	– Create suggestions for standard approaches and/or templates for development and maintenance of user documentation, including user notifications. – Create social platforms for users that contain information about specific GS providers and Frequently Asked Questions. – Provide to users—both those under contract and not under contract—a prompter notification of GS providers' planned or actual capability changes.

D3-B2.3	**Challenge or Lesson Learned:**	**The government and some commercial organizations provide software tools to address GS interfacing functions. If these tools can be utilized and adopted for development of SmallSat mission GS, significant capabilities will be implemented, and potential time/risk/cost savings will result. However, little support and infrastructure exist to support adoption of these tools.**
	Rationale:	Significant time and resources are often required to leverage existing software tools due to a lack of awareness, user documentation, and training.
	Suggestions or additional comments:	– In partnership with academic organizations, the government creators of GS software tools should establish workshops and/or training courses for users of those tools – A greater awareness of GS software tools should be cultivated, possibly through the inclusion of GS tools in S3VI's SmallSat Parts On Orbit Now (SPOON) Database, which consolidates NASA and other entities' databases on small spacecraft parts, technologies, and other information.
D3-B2.4	**Challenge or Lesson Learned:**	**There is a shortage of appropriately equipped GS and operational capabilities for cis-lunar communications, navigation, and tracking.**
	Rationale:	Use of the cislunar domain by business, technology, exploration, and science interests, is expected to significantly increase in the U.S. and internationally
	Suggestions or additional comments:	– Compared to LEO GS capabilities, availability of government, commercial, and academic Deep Space Network (DSN)-type GS capabilities is very limited. All three potential GS provider sectors should expand to help meet the new cis-lunar demands. – Upgrades to existing DSN GS are costly, partially due to the lack of COTs parts.
D3-B2.5	**Challenge or Lesson Learned:**	**During the proposal and early implementation stages, new potential SmallSat mission projects have very few staff that have experience with the GS support of a SmallSat mission or even a traditional spacecraft mission.**
	Rationale:	It is important for new missions to have GS definition support early during the mission concept definition, mission requirements development, design, I&T, and operations phases.
	Suggestions or additional comments:	– Establish more opportunities for "How to" workshops and forums to provide introductory information about GS support. – Provide opportunities for reflective discussions (like this forum) that focus on lessons learned and frequently asked questions.

5.6 Data Processing System (Day 3, Session B3)

Session overview:

This session focused on data processing during Phase D mission integration and testing. Session participants discussed the type and frequency of data that should be recorded during I&T. Participants agreed that the characteristics of the onboard science instruments dictate the types of science data collected during I&T, but the engineering team should optimize the housekeeping data collected. Strategies to do so include ensuring that accurate records of each test are maintained (e.g., software version used, noting which switches are on/off, etc.), tracking the current drawn, recording events to determine which segment of the software is being exercised during the test, etc. Although the ideal cadence for collecting housekeeping data will differ for each mission, capturing as much information as possible during testing (e.g., setting the event filter to "debug" during testing) is optimum and helps ensure that correlations can be made with on-orbit performance later. In addition, high-frequency data logs from testing can be useful to assess lower-frequency data obtained on-orbit.

The group discussed advantages and disadvantages to processing data onboard vs. on the ground. For SmallSat missions where science instrument data is crucial, it is optimal to record all raw data (Level 0) and do the Level 1 processing onboard. CubeSats, however, have less onboard data storage and must implement a different data storage strategy. It is best practice to ensure the science team understands the capabilities of the spacecraft so that they can prioritize the different types of data and determine whether the data should be processed onboard or on the ground.

Sometimes telemetry data collected during testing ends up being more valuable to the science team than the engineering team. Likewise, the science team can sometimes help the engineering team decipher test results, so coordinating with the science team and sharing test results throughout the testing process can be beneficial.

In addition, participants examined ways to ensure test results remain comparable, even though data products change during the testing period and up to launch. Strategies include ensuring the I&T data products are identical to on-orbit data products and collecting as much data during testing as possible to enable correlation with on orbit performance/conditions (e.g., to understand environmental effects).

The team also discussed products that can help ensure test data is easy to view and interpret (e.g., the COSMOS user interface) and various data storage methods (e.g., using Google Drive, storing data at the Mission Operations Center).

Session notes organized by challenges and lessons learned:

D3-B3.1	**<u>Challenge</u> or Lesson Learned:**	**What housekeeping data should be recorded during I&T?**
	Rationale:	The experimental data collected during I&T depends on the characteristics of the instrumentation, but engineers must decide how to collect housekeeping data to optimize experiment value.

	Suggestions or additional comments:	The I&T team should: – Document the software version that is being used before the test starts. – Record all power system telemetry, including switches that are on or off. – Keep track of the current that is drawn during the test run. – Record events to determine which segment of the software is being exercised during the test. – If bandwidth is limited, use flags to encode the status of different subsystems during the test. – If possible, use one data point for multiple subsystems. For example, attitude and position data can sometimes be used by more than one subsystem. Make use of interpolation to enable the same data point to be used by an instrument and the general bus.
D3-B3.2	**Challenge or <u>Lesson Learned</u>:**	**What is the right cadence for housekeeping data?**
	Rationale:	Collecting different rates of housekeeping data may be useful to test nominal operations vs. troubleshooting an anomaly.
	Suggestions or additional comments:	– The optimal cadence for housekeeping data is different for each satellite component. Typically, a 1 Hz cadence is employed for housekeeping data. It is best to try to record every housekeeping message that is generated during I&T. Often the attitude control loop runs at a different speed (e.g., 5 Hz). While attitude control generally is not part of the housekeeping on-orbit, it is recorded during I&T. – Event filtering is a useful tool: strings with status flags (e.g., error, debug, information) are generated for the telemetry stream. Depending on the filter's status setting, strings with the matching status flags will be put onto the telemetry stream. Typically, the filter will be set to "debug" during testing to obtain as much information as possible. The filter level can later be changed on-orbit if a problem needs to be debugged. – If you know the frequency at which an instrument or component runs or the frequency the principal investigator wants, record at that frequency (or as close as possible to the on-orbit frequency) during testing. – During ground testing, record everything at the highest rate possible and log as much information as possible to help with debugging. It is useful to know how often faults are occurring for troubleshooting, so log the number of times an issue or error occurs. – It is useful to have higher frequency logs from test to compare with lower frequency logs on-orbit. This comparison can be used to determine if the recorded flight data can be accurately interpolated.

D3-B3.3	**Challenge or Lesson Learned:**	**How do you determine what is processed onboard vs. ground post-processing?**
	Rationale:	There are advantages and disadvantages to processing data onboard vs transmitting it to the ground for processing.
	Suggestions or additional comments:	– For a mission where instrument data is important, record all raw data (L0) and then process it onboard to L1. For larger missions, one day of L0 data can be approximately 100 gigabytes (GB) and the L1 data will be 5 GB after processing. Sometimes early on, a mission will downlink all the L0 data recorded from the beginning of the mission. The mission will identify any triggers or science products (e.g., forest fire) by processing onboard. This process would generate L2 data that is only a few bytes. – One large mission has a heterogeneous computer with a central processing unit (CPU), graphics processing unit (GPU), and two 128 GB drives. All the data from one day is stored on one drive and the second drive contains a backup of that data. The ratio of downlink time to processing time is 2:1. Unfortunately, CubeSats do not have this much storage, even though they have many instruments that provide a large amount of data. – CubeSat rule of thumb: Raw data from science instruments, sensors, or actuators that is used for limit checking or health and safety of the spacecraft is stored for onboard processing. Critical flags in the raw data are checked as they arrive and stored in the housekeeping data, then passed on to the mission team (e.g., flags that indicate whether science instruments can continue to be powered or operated or if there is an issue with the spacecraft that needs to be addressed). Some raw telemetry data that does not need to be processed is stored separately so it does not consume processing time. Floating point data is sent as raw data to the ground when the SmallSat does not have hardware floating point support. In this case, processing time is saved because ground-based computers can process floating point data much faster than onboard computers. – Best practice is to inform the science team about the limitations of the spacecraft (bandwidth, storage capacity, thermal impact of compute time, etc.). Then the science team can prioritize data and create requirements to indicate whether the data should be processed onboard or if it should be sent to the ground as raw data. Work with the instrument, spacecraft, and Mission Operations Center (MOC) teams to define the science products and to establish and document Data ICDs.
D3-B3.4	**Challenge or Lesson Learned:**	**Communications between the engineering and science teams can greatly facilitate the efforts of both teams.**
	Rationale:	

	Suggestions or additional comments:	– There is a real difference between these two types of data products. On the engineering side, there are correlations in the data that can be useful, but often this information is not known before the mission starts. Sometimes telemetry data that the engineering team did not need was actually found to be useful to the science team. For example, thermal data collected by the engineering team was useful for determining how science instruments were affected by environmental conditions and external disturbances. It is beneficial to provide the science team with as much information as possible. – It is challenging for the engineering team if they do not have the science instruments early in the integration process. To mitigate this issue, the team can use simulated data from the instruments so data processing can be developed well before I&T. – Someone from the science team should be in the room or readily available when the engineering team is conducting I&T. In one case, the engineering team thought data generated during I&T was bad, but actually the documentation they were using was incorrect. – As part of the functional and comprehensive checks it is useful to run the payload, then send the data to the science team to be sure nothing changed in the payload. The engineering team should send data products to the science team as testing progresses to be sure the results are what they need and/or expect.
D3-B3.5	**Challenge or Lesson Learned:**	**It is easy to collect a lot of data during I&T, but it is of no use if the data are hard to compare or never used.**
	Rationale:	Searchable data and context-aware trending are important. What tools have been used or are suggested to address this issue?
	Suggestions or additional comments:	– One team started using Ball Aerospace's COSMOS ground system (an open-source user interface for command and control of space systems), which has a database that is easy to parse. The science team is required to provide scripts to parse the data and plot it. Plots are posted in Microsoft Teams and can be compared weekly to see variations.
D3-B3.6	**Challenge or Lesson Learned:**	**As data products inevitably change during the I&T period and the time leading up to launch, how do you ensure test results are comparable?**
	Rationale:	
	Suggestions or additional comments:	– Record everything from I&T and have every subsystem turned on. Be sure the data products from I&T look exactly the same as they will on orbit, even though subsystems are not turned on and off while on orbit. Document all data products. Look at the data during mission simulation to determine if the data looks good. Collect as much data as possible to correlate with conditions that might look different on orbit. Correlations will also be useful to understand environmental effects.

D3-B3.7	**Challenge or Lesson Learned:**	**What is the best place to store data collected during I&T?**
	Rationale:	
	Suggestions or additional comments:	– Some missions put a portion of the data onto a shared Google Drive. All the recorded data is stored at the Mission Operations Center (MOC). If the mission is going to run Comprehensive Performance Tests (CPTs) the COSMOS file is included with the signed off handwritten procedure documents.

6. Phase E and F Operations, Sustainment, and Closeout (Day 4)

The fourth set of workshop sessions focused on mission phases E and F. These phases typically include activities related to commissioning and operations on orbit, data archiving and analysis, dissemination of results, and the final steps of decommissioning and closeout at the end of a mission. A total of six topics were discussed in these sessions, including operations, on-orbit anomalies, extended operations, and data processing. The information captured in this chapter can benefit projects as they implement missions and NASA management as it formulates policies.

Establishing first contact and successful communication remains a major challenge for many SmallSat missions, along with the fact that radio malfunctions are one of the most common failures to occur early in a mission. Designing the radio to turn on automatically without receiving a signal from the ground, carrying backup communication systems, planning for access to backup ground stations, and practicing commissioning activities with both primary and backup systems ahead of time are some best practices recommended to mitigate communications issues. While the advent of many higher frequency (S- and X-band) radios for CubeSats offers the possibility of high-data-rate telemetry, such radios involve stricter requirements for pointing control, which may further complicate the initial contact.

The addition of simple sensors, including diodes and cameras, can greatly aid in the verification of basic functionality of the spacecraft as well as successful deployment of extendable structures. Data from these sensors can also be critical for identifying, correctly diagnosing, and mitigating any anomalies that might occur. Another potentially mission-saving practice is to implement a flexible design that allows operators to request more detailed telemetry for each subsystem, if needed for verification or fault detection. Finally, carrying out regular system reboots can help mitigate latch-ups and other radiation effects or other failures.

It is becoming more common for SmallSat missions to remain operational and fully functional beyond their design lifetimes. Such missions offer great opportunities to enhance scientific, technological, and educational return. While extended operations often require only modest amounts of additional funding, the feasibility depends on a variety of factors, both technical (e.g., any changes needed to the spacecraft, payload, operations, licenses, etc.) and programmatic (e.g., operational funds remaining, the additional scientific, technological, or educational benefits that could still be gained, etc.). Options to receive additional Phase E funding vary greatly amongst projects and divisions at NASA and clear guidance and a responsive process are urgently required. Likewise, ready access to funding for Phase F activities to optimize the returns from a mission is also needed.

Many PIs struggle to access to adequate expertise and resources related to the processing, storage, and sharing of mission data. Guidance from NASA on data standards and the implementation of best practices regarding data processing, storage, and sharing (along with templates and examples) would benefit SmallSat missions. Leveraging commercial cloud solutions for data storage and processing creates major efficiencies, particularly for collaboration and sharing of data. However, some program restrictions within NASA inhibit these options.

All sessions highlighted the importance of sharing solutions and best practices across missions and encouraged NASA to continue its support for efforts such as this SmallSat Forum and the S3VI. The creation of a SmallSat mentoring program was also suggested to further facilitate knowledge transfer among missions.

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6.1 Operations Management (Day 4, Session A1)

Session overview:
The focus of this session was the project-management aspect of operations, sustainment, and closeout. Topics discussed included staffing for operations, automation of operations ("lights off"), budget and schedule for commissioning activities, management of ground assets, and the role of the science team in nominal operations. Key takeaways from the discussion include the following:

1. Automation will be needed for many long-duration missions, but missions should take care not to automate too early in the development phase, because that can make a mission less flexible and/or cause a need for redesign later in the lifecycle.
2. Plan plenty of time to practice commissioning activities; do not underestimate how much time commissioning will take and how important the practicing is to the success of the mission. One of the most challenging aspects of commissioning is locating the satellite. In addition, make sure that backup ground assets are online during practice sessions, and that test engineers are available if needed for troubleshooting.
3. Ideally, the design will employ a radio that is compatible with many ground stations.
4. Lessons learned about staffing for operations include: rotate who is on call each week for unmanned operations; for manned staffing, identify a core nominal team that consists of multiple persons, employ a normal daily routine, use a checklist, and ensure a separate team of experts is on standby for troubleshooting.

There was not consensus regarding inclusion of scientists on the operations team. In some cases, it is key to success of the mission to have scientists in the loop, but the role scientists should take depends on the mission, available resources, and the scientists themselves.

One thing that was clear from the session was that NASA could benefit from gathering and passing on the many lessons learned and best practices established by experienced small spacecraft teams.

Session notes organized by challenges and lessons learned:

D4-A1.1	**Challenge or <u>Lesson Learned</u>:**	**The level and makeup of staff needed for operations depends on mission-specific factors**
	Rationale:	Several factors affect staffing needs including: the experience level (expertise), how much data is needed (complexity), the type of mission, and how often contact with the spacecraft will be made Academic teams may be larger than NASA teams because they incur lower costs. Access to experienced mission operators who can train students on how to operate the satellites is an advantage. Missions managed from a center require a mission operations manager. For example, RaInCube, JPL managed the RaInCube mission, but the mission integration work was contracted out. It was vital to communicate to the sponsor and to NASA about how the mission was progressing. A mission operations manager was assigned, but the role had not appropriately been scoped. The function was estimated at about 0.1 full-time equivalent (FTE), when in reality the effort required was close to a full FTE.

	Suggestions or additional comments:	– It is helpful to identify the core normal team and to simulate days in the life. – One should plan for an intensive (24-7) commissioning period that lasts about a month.
D4-A1.2	**Challenge or Lesson Learned:**	**One of most challenging aspects of commissioning is locating the satellite.**
	Rationale:	Orbit information and predictions can be highly uncertain and for groups of satellites being deployed together, it is particularly difficult to determine the individual orbits for all objects.
	Suggestions or additional comments:	To help mitigate this issue, missions can: – Register with the 18th Space Control Squadron – Exchange contact information with the PMs of other payloads on the same launch vehicle
D4-A1.3	**Challenge or Lesson Learned:**	**Establish a rapid reaction team for when there are problems or issues that need to be quickly addressed; it is also critical to remain in contact with the engineering staff**
	Rationale:	While nominal operations can be planned well in advance and can typically be done by a single person, commissioning or troubleshooting requires all of the applicable system leads/experts to participate or at least be on call.
	Suggestions or additional comments:	– Ensure all of the experts are on standby in case something goes wrong and obtain their contact information so they can be reached during incidents – Schedule reviews during the operations phase that are carried out by a core set of mission team members to identify any problems or lessons learned that may occur – Commissioning should proceed quickly, but quite often it does not; be patient and handle any adversities that may come up
D4-A1.4	**Challenge or Lesson Learned:**	**Establish an operations concept early and practice both commissioning activities and nominal operations**
	Rationale:	On the Miniature X-ray Solar Spectrometer (MinXSS) mission, the students developed the commissioning scripts about three months prior to delivery so they could practice the scripts with the actual satellite. After delivery of the spacecraft the commissioning scripts were practiced multiple times during the month before launch, using the flat-sat. The Electron Losses and Fields Investigation (ELFIN) team started preparing for operations almost eight months before delivery, but even that was believed not to be early enough.

	Suggestions or additional comments:	– Employ the same team to do the testing and simulations and perform the commissioning activities – Ensure all of the experts are on standby in case something goes wrong – The period of time between commissioning and nominal operations is crucial. During this baseline operations period, a team should determine the tweaks that need to be made to optimize operations.
D4-A1.5	**Challenge or <u>Lesson Learned:</u>**	**Automated ("lights off") operations may not be the right choice for single, short-lived missions, but is needed for constellations and may be beneficial for long-lasting missions with a small mission team.**
	Rationale:	Whether automated operations make sense depends on the mission – the number of satellites, length of time in operations, and number of passes to support. The only way automation is worth the investment is if it is cheaper than paying an operations staff. If you only have a single mission, it might make more sense to staff the passes rather than trying to automate operations. However, for a small team, which is often the case for CubeSats, it would be exhausting to support normal operations for more than a few weeks. Passes can occur at any time during the day/night and shift slowly over time. For these cases, "lights off" operations are recommended. For organizations with a lot of missions using compatible hard-ware, automation has proved to be very effective. Benefits of automation include: fewer staff are needed and the method used to downlink data is more consistent, resulting in more data downlinked Drawbacks of automation include: one must develop autonomous operation software (planning tool, scripts); special operations/commanding are at higher risk of needing additional passes if any of the commands are missed by the automated operations system. If a mission is operating for several years, then automation should be employed, if possible. However, automating too early in the lifecycle can result in a less flexible mission. Some aspects of a mission will not become apparent until the mission is operating on orbit.
	Suggestions or additional comments:	– Developing a checklist of activities that need to occur during mission operations is important – "Gamifying" operations, e.g., by visualizing tasks and progress on the screen, can make the team more excited and help prevent attrition
D4-A1.6	**Challenge or <u>Lesson Learned</u>:**	**Successful ground asset management is critical to small satellite missions**

	Rationale:	Ground assets are extremely important – if they are lost, there is no mission.
	Suggestions or additional comments:	– One recommendation is to have a backup ground station as well as spare parts for ground station repairs. – When building a CubeSat, select a radio that is compatible with many ground stations to allow for flexibility.
D4-A1.7	**Challenge or <u>Lesson Learned</u>:**	**Science team participation in nominal spacecraft operations can be necessary and beneficial, but experiences are varied, and potential consequences should be carefully weighed.**
	Rationale:	Participants agreed that for operations, generally the scientists tell the engineers what to do, and then the engineers do it. For example, the HaloSat science team conducted the science operations planning—which was limited to providing exact times and quaternion attitudes for observation targets. This information was then provided in scripts, which were compiled into the operations scripts by the MOC. Participants also agreed that it is important in operations to consider the perspective of scientists and to train the operators to read the science reports. In addition, several arguments and examples were offered both in favor of and against using the science team more directly for operations. Potential benefits include: Scientists can fill in when student members of the operations team are unavailable. For example, some of the MinXSS scientists were heavily involved in spacecraft operations. A large part of their role is training and managing the students and filling in gaps when students went on vacation or had finals. The scientists can also ensure that the right experiments are made, which helps in the planning. Involving scientists in operations can facilitate communications between the science and operations teams. For example, on the Massachusetts Institute of Technology Haystack Observatory team, scientists are embedded in the operations. This practice ensures the mission obtains the data required. The scientists understand the limitations of the spacecraft so they can communicate their needs without stressing the operations team. Potential drawbacks include: Operations can be time consuming early in the mission and so science analysis by those scientists helping with operations is delayed. Every team is strapped for time and talent, so it may be more beneficial for the scientists to focus on their own tasks. Finally, scientists may not have the required experience. There is certainly nothing that would prohibit scientists from supporting flight operations, but they must be both willing and able to do so.

	Suggestions or additional comments:	

6.2 Engineering (Day 4, Session A2)

Session overview:
This session focused on the engineering aspects of operations. Topics discussed included how to identify and design core telemetry for performance verification and how to ensure successful implementation of critical components such as radios and ground stations.

Participants shared lessons learned from many recent and current CubeSat missions. Establishing first contact and successful communication were recognized as major challenges, along with the fact that radio malfunctions are one of the most common failures to occur early in the mission. Options for carrying backup communications systems were discussed, including alternative solutions such as Globalstar or ham radios, which can provide limited telemetry for commissioning and fault detection. Designing the radio to turn on automatically without receiving a signal from the ground was presented as a best practice, along with transmitting a beacon signal to help locate the satellite, especially if it was launched with many others. Similarly, designing and planning for potential ground station back-up solutions were also considered best practices. The advent of many higher frequency (S- and X-band) radios for CubeSats offers the possibility of high-data-rate telemetry, but at the expense of added requirements for pointing capability.

Session participants also discussed best practices for prioritizing data downlink for telemetry. Sensors and telemetry onboard should be designed based on the specific needs of the mission and critical technology, e.g., cameras or diodes to verify deployment of extendable structures. Building flexibility into the design—including the capability to request more detailed telemetry for each subsystem if needed—was also regarded as sound advice.

Session notes organized by challenges and lessons learned:

D4-A2.1	**Challenge or <u>Lesson Learned</u>:**	**Consider carrying a second radio**
	Rationale:	Radios are one of the most common failures on CubeSat missions (especially for those that are Dead on Arrival [DOA]). Adding a second radio can be a mission-saver, but tradeoffs in terms of size, weight, power, and cost (SWaP-C) and mission complexity must be carefully considered. A second radio may also require additional frequency licensing. Globalstar or Iridium may be good options, since they do not require separate licensing and can deliver some limited data for early diagnostics. Another good option is a ham radio, which can serve as a beacon and offer invaluable help in establishing first contact through the global ham radio community.
	Suggestions or additional comments:	– Make sure that the radio turns on automatically after deployment rather than waiting for a ground command – Thorough testing with the ground station(s) in flight configuration before launch is critical to prevent communication failure

D4-A2.2	**Challenge or Lesson Learned:**	**Plan for ground station backup solutions in the case of outage or failure**
	Rationale:	The Wallops 18m dish ultrahigh frequency (UHF) ground station has been a workhorse for the technology demonstration CubeSat community, but it was down for several months with hydraulic issues and several missions were relying on it; as a result, those missions had no means of communications from November 2020 to March 2021. This example serves to illustrate why planning to use more than one ground station is highly preferable. Appropriate backup solutions are hard to identify and implement in a timely fashion so preparation and planning during mission design is essential.
	Suggestions or additional comments:	Kongsberg Satellite Services (KSAT) light and NASA's Near Earth Network (NEN) networks are other proven options for secure ground station solutions
D4-A2.3	**Challenge or Lesson Learned:**	**Many solutions are emerging for CubeSat radios in X- and S-band**
	Rationale:	Higher-frequency radios can greatly enhance the data download capacity. However, higher frequency radios require better pointing and attitude control, which must be considered in the design. Similarly, ground stations require more precise knowledge of spacecraft location to achieve lock when these higher-frequency radios are employed.
	Suggestions or additional comments:	
D4-A2.4	**Challenge or Lesson Learned:**	**The critical parameters to monitor for performance verification will emerge from testing**
	Rationale:	Limited telemetry available for download means that prioritization and planning are essential. Thermal vacuum (TVAC) and day-in-the-life testing offer the opportunity to simulate expected ranges of performance and determine which parameters are most critical/important for verification.

	Suggestions or additional comments:	– Mission planners should think about what can go wrong and ensure the telemetry provides the right information to investigate issues. Key parameter lists should be obtained and kept for each subsystem. – Another best practice is to ensure that all telemetry is available for all subsystems via command; telemetry should not only include the daily housekeeping, but enough detailed information to help troubleshoot all subsystems – Default telemetry should include a single crosscutting packet that goes across subsystems. This packet should contain basic spacecraft health information such as the mode of the spacecraft, the boot count of the spacecraft, whether any alarms have tripped, or if any watchdog counts incremented. In addition, the packet should have information about solar panel health (such as battery charge, body rates and quarternions), the stability of the reaction wheels and how close to the maximum rate they might be, radio health and status (such as received signal strength), and the temperatures of key components and any key current sensors.
D4-A2.5	**Challenge or Lesson Learned:**	**Consider including onboard diagnostic sensors in the spacecraft design**
	Rationale:	Simple cameras, diodes, or the like can provide additional crucial confirmation regarding deployment of extendable structures and other critical system operations during commissioning. For example, on the Marco mission, photodiodes were used extensively; 8-12 of them were strategically placed around the spacecraft under solar panels or under antennas to verify deployment. Marco also employed small engineering cameras to observe deployment of the foldable high-gain antenna. The same was done for deployment of the RainCube mission's antenna (first active radar).
	Suggestions or additional comments:	

6.3 Data Processing (Day 4, Session A3)

Session overview:
The focus of this session was data processing for small spacecraft missions in phases E and F. A number of challenges were identified, but session participants recommended several solutions that have been proven successful on previous SmallSat missions.

One of the major suggestions voiced was to leverage cloud storage for data storage and processing. This practice creates major efficiencies, particularly when it comes to collaborating on and sharing data. However, participants also noted that program restrictions within NASA make cloud storage difficult when collaborating with external parties. Additionally, session participants noted the importance of considering data processing methods early on in each mission.

In addition to the specific challenges and lessons learned listed below, there was great discussion on the role session participants felt NASA should have in setting data standards (and implementing best practices) for data processing, storage, and sharing. The group agreed that they were leery of NASA setting the standards, but instead felt that NASA should work with other organizations that set standards (e.g., industry, DoD, etc.) and give a stamp of approval versus taking the lead. They also felt that NASA should issue guidance in the form of examples. The group also emphasized that conferences such as this forum enable missions to share information on data standards and best practices for adopting and utilizing them, and that it is vital that resources pertaining to data standards be widely available to PIs.

Session notes organized by challenges and lessons learned:

D4-A3.1	**Challenge or Lesson Learned:**	**Challenges exist in storing and disseminating level zero data, but cloud storage is recommended as an effective best practice for data storage and sharing.**
	Rationale:	There are many options for storing and disseminating mission data and some work better than others. Cloud storage has proven effective across multiple missions in easing common barriers. If there are multiple instrumentation groups or institutions involved, missions can conduct data processing in a more piece-meal fashion, and host data at various places, versus in a centralized data center. Centralized Science Data Centers (SDC) can pose issues; depending on how large a data set is, it can be difficult for the institutions doing the processing to get data to the central SDC. Some teams have had to ship hard drives, rather than rely on data pipelines, because pipelines can also become stressed when multiple users access the data. Using websites to store and disseminate data has been challenging, as well. Using cloud storage has been working well lately, specifically using Box. Cloud storage gives users at various sites access to the level one data. The ground station uploads the data directly to the cloud storage system and users can pull data directly from there. Example missions successfully using cloud storage include the Scintillation Prediction Observations Research Task (SPORT) mission (working with Brazil) and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC 2) mission, which has been using Box.
	Suggestions or additional comments:	– Using the cloud’s capabilities to process data in the cloud itself, versus just using the cloud for storage, is a desired future capability. – Missions should archive level zero data in the natural binary state; this practice allows storage of the raw data and development of processing tools that work directly with the level zero data.
D4-A3.2	**Challenge or Lesson Learned:**	**PIs collaborating directly with NASA on data processing or data management often experience many challenges due to NASA restrictions.**

	Rationale:	Too many existing program restrictions within NASA create barriers that prevent PIs from efficiently collaborating on data management and processing. The factors driving this challenge reside primarily within NASA, but the challenge greatly affects projects that involve collaboration between NASA and external institutions. For example, at NASA Langley Research Center, most data must be vetted through the PI. In one example, the PI had to physically travel to a NASA Center to access the data, but the PI was not located near any NASA Center. This example emphasizes the difficulty in sharing NASA data with collaborators. NASA's large file transfer (LFT) system was successfully used to send the PI some data in this example, but the PI still had to send an email to request specific data. This arrangement is not optimal because one does not always know what data is available from the spacecraft. (Note: NASA's LFT capability was since retired, and replaced by Box, which can be used to share large data files.)
	Suggestions or additional comments:	
D4-A3.3	**Challenge or <u>Lesson Learned</u>:**	**Consider the data processing chain early in the mission.**
	Rationale:	Ensuring mission data processing systems are thoroughly thought through in the beginning will help mitigate potential problems later in the mission life cycle. The importance of this strategy begins in the engineering phase. Session participants cited one example where the mission team would lose its time base when the spacecraft would reset, resulting in timestamps resetting to zero. A similar example regarding timestamping of data occurred on the Shields CubeSat mission: The Shields team implemented a time checking routine to work through discrepancies and errors caused from the CubeSat resetting and timestamps reverting to an arbitrary number. The above examples illustrate how missions would benefit from thinking about the timestamping and processing of data—including ancillary data needed to interpret and use the data—early in the mission lifecycle.
	Suggestions or additional comments:	– Many data processing capabilities will depend on the hardware the mission is employing. Therefore, managing the data in a way that is universally acceptable to all missions is challenging.
D4-A3.4	**Challenge or <u>Lesson Learned</u>:**	**Code documentation is recommended rather than file documentation for data processing, but final data files should be produced for the archive at project closeout, since code can become obsolete with time.**

	Rationale:	Code documentation is more transparent than file documentation because it enables one to review the code, itself, and the routines used to process the data. However, code can be updated multiple times and there is not an obvious way to compare it with the data that has been already downloaded—meaning the raw data might need to be re-processed, which is not always possible. In contrast, when working with pre-processed data files, it is obvious when there have been revisions to a file because one can see it in the file. With pre-processed data files, the trade-off is that the data processing is more of a "black box." Good documentation of the data processing approach and implementation is essential in either case.
	Suggestions or additional comments:	– Documentation, whether for code or files, requires a lot of resources and may be difficult for small projects to accomplish
D4-A3.5	**Challenge or Lesson Learned:**	**Accessing resources and data standards (including best practices) regarding data processing is a challenge for PIs.**
	Rationale:	Some data processing resources exist at various NASA centers, but they may not all be openly shared and current hosting platforms are not conducive to efficient consumption for PIs. Clear data standards documentation and effective dissemination (Consultative Committee for Space Data Systems [CCSDS] data standards were cited as an example) will be required for the community to adopt such standards, even if the standards are excellent. People will only use standards if they can easily access them.
	Suggestions or additional comments:	– There is a need to provide accessible guidelines and templates, and to point PIs to those both as part of the solicitation process and when rejecting proposals due to weaknesses in the data management plans. – The S3VI website was cited as a helpful resource, but session participants noted that the website is not optimally organized.
D4-A3.6	**Challenge or Lesson Learned:**	**Small programs should leverage existing infrastructure as much as possible to process and disseminate data.**
	Rationale:	Small programs do not have as many resources as larger programs, so using existing systems is recommended instead of developing new data processing and dissemination infrastructures. The SPORT mission was cited as an example where a project successfully leveraged existing infrastructure: Brazil has a space weather data center that disseminates data, and the SPORT mission team works with this center to disseminate data.
	Suggestions or additional comments:	

6.4 Extended Operations (Day 4, Session B1)

Session overview:
This session addressed issues related to extended (Phase E) operations for CubeSats. CubeSats are typically developed on a very lean budget that is focused on delivering to launch. Given their inherent risk, success for a CubeSat mission mostly assumes only a fairly short mission lifetime. On the other hand, it is becoming more common for these missions to remain fully functional beyond their design lifetimes, offering great opportunities to enhance scientific, technological, and educational returns. While extended operations often require only modest amounts of additional funding, the feasibility depends on a variety of factors including: what type of changes (if any) are needed to the spacecraft, payload, data rate, downlink or uplink, etc.; how much operational funding remains (if any); whether the proposed goals have been achieved; whether the science benefit outweighs the additional funds needed; whether there are educational benefits still to be gained; etc.

This inherent uncertainty in expected lifetime and operational status is not typical of NASA missions, and the panel discussed how to obtain optimal outcomes for this type of mission in the face of this reality. Session participants concluded that there is a strong need for a clear and responsive process from NASA Headquarters to fund extended CubeSat operations. A new 'Junior Review' approach may provide a model for how to achieve this objective.

Session notes organized by challenges and lessons learned:

D4-B1.1	**Challenge or Lesson Learned:**	**CubeSat missions should plan ahead for extended operations**
	Rationale:	Planning ahead for extended operations will make implementing any changes much easier. In recent years, it has become more common for CubeSat missions to still be active one year in-orbit after initial objectives have been met, and an extended mission is a great way to collect more science data. For example, the ELFIN mission never planned for an extended mission, but was able to work with a Japanese startup (Stellar Station) to get six additional passes per day for data downlink during a highly successful extended mission lifetime. They also were able to reconfigure science instruments and flight computer in-orbit to take advantage of this additional data download capability and to redirect emphasis from instruments that did not function as well on-orbit to others that did.

	Suggestions or additional comments:	– Both HaloSat and IceCube had extended missions and nothing new happened; they just got more science data from space for longer. The only issue was to secure funds for additional operations. – In general, participants noted that the ability to reprogram in-orbit is very beneficial to CubeSat missions and has saved several missions (e.g., Dellingr and ELFIN). Therefore, it is recommended that software is designed to be patchable and/or utilize table-based changes whenever possible. This practice will help the mission respond to changes in spacecraft or instrument performance, and in some cases may help save the mission in case of unanticipated failure modes.
D4-B1.2	**<u>Challenge</u> or Lesson Learned:**	**The NASA funding process for extended CubeSat mission operations is opaque, at best.**

	Rationale:	Due to their inherent risk of failure and limited budgets, CubeSats typically enter Phase E operations with very little funding. If the CubeSat remains operational at the end of its designed lifetime, it can be difficult to receive additional funds quickly for continued operations. There is currently little guidance from NASA on how to receive additional Phase E funding. The processes used by various projects and divisions are different and involve various paths to take depending on the timing and mission. If a mission is operating and getting great science, the process for securing funds for an extended mission can be easy. Funding will always be a limiting factor and the risk of aging satellite components needs to be considered. One way to obtain additional funding for extended operations is to re-propose, which is common in the Astrophysics Division. However, the MinXSS-2 mission had several proposals rejected before finally securing additional funds through a grant. The timing of grants is not compatible with a CubeSat timeline as the typical waiting period to receive the additional funding is comparable to the extended mission itself. The HaloSat mission had success with good timing in that they received the award before nominal operations stopped. Another way is to get a No Cost Extension (NCE), which only requires the PI to submit a request that requires no additional funds. Missions that need more funds can submit an augmentation request that breaks the number of hours down with how much work is involved. This is the route ELFIN took to secure additional funds; the ELFIN PI submitted a letter describing the good science data that was being collected, the papers that were being written, and the longer lifetime expected, and received more funds. ESTO employs a 'wait and see' approach, where requests for additional funding for successfully operating missions may be granted for a year, and then progress reports are submitted quarterly for additional funding. This solves the issue of timely replenishing of operations funding, while also not committing NASA funds to a mission that is no longer operational. This approach serves as the basis for a new 'junior review' concept that is being considered by NASA Headquarters. However, the specific implementation and decisions are made by individual divisions and programs. One suggestion was to include plans for extended operations in the original proposals, but this raised concerns about adding this burden on proposers who often already struggle with the proposal process.

	Suggestions or additional comments:	– Participants recommended that missions first contact Program Scientists at NASA Headquarters to determine the available options for obtaining additional funding for extended operations – MinXSS went through several different iterations, including proposing to ROSES. However, the ROSES timeline is not aligned with the CubeSat on-orbit timeline – i.e., the CubeSat could fail or deorbit within the proposal and review timeline. The community does not recommend using ROSES as an extended operations funding vehicle. – Regarding 'junior review,' CubeSats are operated on a shoestring budget, often with heavy student involvement. Any extended funding process should take these considerations into account.
D4-B1.3	**<u>Challenge</u> or Lesson Learned:**	**Licensing issues may arise during extended operations**
	Rationale:	During extended operations, a mission may be required or desire to use additional ground stations, which the existing license may not allow. In addition, licenses can expire. For example, in its extended operations RainCube wanted to contact more ground stations than its license permitted. Shifting from KSAT stations to Amazon Web Services (AWS) stations would have allowed RainCube to contact more ground stations and collect more data. The process to get proper licensing in place for this shift took almost a full year and RainCube de-orbited four days later. Part of the delay could have been due to the need for coordination through the International Telecommunication Union (ITU), which is important to be aware of.
	Suggestions or additional comments:	– Not only extended mission licensing but also the initial licensing process is problematic for CubeSat projects. Participants recommended that missions make communication a commodity to be obtained in a similar way to the launch and deployment. A "CSLI-type of communication program" could make this process much easier to navigate by eliminating the various hoops to go through to obtain a license, assisting missions in figuring out a specific licensing process, helping missions determine how to get a license for a different ground station and/or how to get an extended license, etc. – Participants also recommended using the same frequency for several CubeSat missions using the same ground station(s), which seems to facilitate the FCC licensing process.

6.5 On-orbit Anomalies (Day 4, Session B2)

Session overview:
The focus of this session was on the identification of and response to on-orbit anomalies. Topics discussed included designing spacecraft to identify issues and identifying resources to permit learning from the mistakes others have previously made, as opposed to repeating them. Four primary topics framed the discussion: how to spot anomalies, how to respond to anomalies, how to design a spacecraft system to detect anomalies, and how to share lessons learned.

For spotting anomalies, the group noted that this effort is specific to each particular spacecraft. Designers should be familiar with their systems and consider how to interpret telemetry accordingly. Direct information about all systems is not possible due to telemetry limits, so operators should understand how this limitation impacts anomaly detection and learn to "read between the lines." Operators should also be very familiar with what nominal operations look like so they can quickly identify outlier events (which are potential anomalies).

The group agreed that the response to anomalies should be planned ahead of time and, if possible, simulated on the ground with a high-fidelity flat-sat. For some missions, it may be beneficial to regularly reboot the spacecraft to mitigate or prevent anomalies. The group also agreed that the satellite's radio receiver should ideally never be turned off. First and foremost, missions should check an on-orbit anomaly against any problems or anomalies that occurred in I&T. Session participants noted that this basic practice is overlooked even in large missions or when the operations team has had no connection to the development effort and may not have all the data from I&T.

Session participants agreed that anomaly detection requires cleverness and critical thinking. Designers must balance information fidelity and quantity as bandwidth to the ground is typically very limited. Power draw measurement (like current) was noted as a key parameter. Imagery of deployable components was emphasized as an ideal way to verify status, but the group noted images are challenging to downlink. Smaller-data alternatives may be cleverly placed photodiodes. When designing to enable anomaly detection, missions should prioritize failure modes and address the most critical first in the design and then the rest (as able).

Regarding sharing lessons learned, all agreed that the small spacecraft community is very friendly and collegial. Participants encouraged others to network within the community and reach out to people sooner rather than later, as conversations are far more efficient than reading papers. The SmallSat conference, S3VI sessions, the CubeSat.org mailing list, and the NSF CubeSat forum were all identified as opportunities to exchange experiences and lessons learned.

It was clear that NASA's efforts to host and continue the S3VI are critical to the small satellite community for the role that S3VI plays in consolidating knowledge and helping connect others in the field. NASA should continue to support and advertise S3VI to maximize knowledge transfer across the community.

NOTE: This document summarizes results from the 2021 NASA SmallSat Virtual Forum. It is for informational purposes only and does not specify Agency plans or directives.

Session notes organized by challenges and lessons learned:

D4-B2.1	**Challenge or <u>Lesson Learned</u>:**	**Understanding the normal and expected behavior for the satellite enables the mission team to identify when the satellite is functioning abnormally.**
	Rationale:	If the behavior of a spacecraft during nominal operations is unknown, the mission team will not be able to spot an anomaly. Many times the data available to identify abnormalities will be limited, so it is crucial to read between the lines using the data at hand. Mission personnel need to understand how to use the available data to infer the state of other components that are not directly instrumented. For example, if there are three components that are tightly thermally coupled and only two are instrumented, an unexplained temperature increase in the instrumented units could actually reflect a temperature increase in the un-instrumented component.
	Suggestions or additional comments:	– Access to a high fidelity flat-sat in the lab that looks just like the spacecraft in orbit will help mission developers understand anomalies and test solutions before implementing them on the spacecraft
D4-B2.2	**Challenge or <u>Lesson Learned</u>:**	**Consider regularly rebooting the spacecraft to mitigate or prevent anomalies.**
	Rationale:	Correctly implemented regular system reboots can automatically recover spacecraft in bad configurations. One recommendation was to reboot by default every 72 hours. The Dellingr mission incorporated this practice, which not only saved the mission a few times, but simplified the failure, detection, and correction exercises. Reset was a solution for most of the mission problems. For example: The UHF cadet radio on Dellingr was prone to locking for no apparent reason. It locked both during testing and on orbit and the reset resolved the issue. When the spacecraft is needed for critical science operations or data downlink, the automatic reset can be manually overridden.
	Suggestions or additional comments:	
D4-B2.3	**Challenge or <u>Lesson Learned</u>:**	**Never turn off the radio receiver.**
	Rationale:	Turning off the radio receiver can leave the spacecraft in a state where it is impossible to command. No matter what problem the spacecraft is experiencing, if it cannot receive commands, it does not matter. Therefore, missions should avoid implementing a receiver-off command. Operators should be able to communicate with the satellite at all times, even if it is not always transmitting. If power is a concern, missions should cycle the receivers. Also, consider hardwiring the receiver into the power system so it cannot be switched off.

	Suggestions or additional comments:	
D4-B2.4	**Challenge or Lesson Learned:**	**Use a simple approach for onboard automated fault detection.**
	Rationale:	Onboard automated fault detection can identify and then address faults before they become significant failures. However, complex fault detection may end up causing more problems than it solves. Therefore, session participants recommended using simple fault detection means. Temperature sensors and light sensors have been used in the past to enable a spacecraft to be able to recognize faults on its own. It was also suggested to use a few data fields as basic “trip wires” that cause the system to reset or go into a safe mode.
	Suggestions or additional comments:	– It may be worth spending the effort to monitor current all over the spacecraft and enable the spacecraft to switch systems on and off based on this monitoring.
D4-B2.5	**Challenge or Lesson Learned:**	**Determine a hierarchy of component failures before the spacecraft flies.**
	Rationale:	Knowing what parts of the system are most important to recover will enable the team to keep the mission operating at a basic level to prioritize on-orbit troubleshooting and recovery operations.
	Suggestions or additional comments:	– Participants recommended that mission teams discuss what will be done if an anomaly is encountered. – Knowing what a critical anomaly would look like and having people on call in case it happens can save the mission
D4-B2.6	**Challenge or Lesson Learned:**	**Make use of various helpful existing resources to remain informed and connected to the SmallSat community.**
	Rationale:	Such resources can be a great starting point to obtain lessons learned and connect with others in the SmallSat community. One important resource is SmallSat Conference proceedings, all of which are available online for free. The S3VI provides opportunities for improved communication and knowledge transfer and is a great way for missions to stay informed and connect with others in the SmallSat community.
	Suggestions or additional comments:	– Engaging directly with others in the SmallSat community through verbal conversation is a better way to facilitate relevant knowledge transfer than simply reading papers.

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6.6 Closure, Optimizing Impact, Assessing Outcomes (Day 4, Session B3)

Session overview:
This session focused on the final steps at the end of a mission and how to maximize mission impacts. Topics discussed included scientific and technical publishing, data sharing, knowledge transfer, education and training, and reporting on lessons learned.

Session participants identified numerous challenges including, notably, access to funding for phase F activities to optimize the returns of a mission.

Impacts of small spacecraft missions include not only the scientific and technical advances, but also highly valuable educational outcomes and development of new project management practices. Participants voiced different opinions regarding the challenges related to capturing and sharing science and technology information through traditional publication channels. However, there was broad agreement that no well established avenues exist to collect and disseminate experiences, lessons learned, and best practices related to the educational and management aspects of SmallSat missions.

The PI/PM community could benefit greatly from a centralized resource to collect and share lessons learned on all aspects of a mission, including education and management. Session participants also suggested creation of a mentor system to facilitate knowledge transfer between missions.

Session notes organized by challenges and lessons learned:

D4-B3.1	**Challenge or Lesson Learned:**	**Instrument papers are critical to enable others to use SmallSat data**
	Rationale:	Lack of time and resources often limits the ability to do full calibration and produce higher-level datasets. The goal is to include observational data from SmallSats in relevant data archives and services alongside the data from big missions. However, making SmallSat data available without additional guidance can make it difficult to use. Instrument papers can help overcome this problem and, at the same time, enhance awareness and attribute credit for the mission.
	Suggestions or additional comments:	– Instrument papers can offer important first-author opportunities for students – Such papers can include information on practices (e.g., on component selection, assembly, integration, testing processes, etc.) to provide supplemental guidance on how to use SmallSat data
D4-B3.2	**Challenge or Lesson Learned:**	**Funding for Phase F is often limited, or not available at all**
	Rationale:	Sources for funding extended mission operations, science and technical reporting, and other reporting and close-out activities vary greatly across science and technology program areas. Lack of funding may result in missed opportunities for increasing the return on investment of successful missions. In addition, knowledge transfer can only happen if lessons learned can be identified, captured, and formulated for sharing—all of which require resources that may not be available without Phase F funding.

	Suggestions or additional comments:	– Phase F funding opportunities for successful missions could be made available by augmenting the existing grant/contract or formulating a new proposal to the same program – Most NASA-funded projects have some reporting requirements, but specifics vary greatly and can be highly confusing –
D4-B3.3	**<u>Challenge</u> or Lesson Learned:**	**A system for free and open exchange of lessons learned does not exist**
	Rationale:	Community sharing of lessons learned is critically important for growing and improving the utility of SmallSat missions and technology, but neither a format nor a forum exists to facilitate such exchange. The NASA Engineering Network system tracks lessons learned, but is unfortunately behind a firewall and not publicly available. The new SSRI knowledge base tool at the S3VI may develop to fill this need more broadly.
	Suggestions or additional comments:	– Collaboration with private industry can limit the ability to share lessons learned due to proprietary rights and hesitation to elaborate on failings – Lessons learned documentation does not have to be formal, but recording what was done and what was learned are key. Missions should capture that information and preserve it for posterity so that subsequent missions do not repeat those mistakes or fall into those same pitfalls, and can benefit from what previous missions have learned.
D4-B3.4	**<u>Challenge</u> or Lesson Learned:**	**A universal system for sharing experiences regarding project management and processes is not in place**
	Rationale:	CubeSat and SmallSat missions not only develop and utilize new technology, but also new management approaches, processes, and procedures. Community sharing of lessons learned and best practices for these aspects is a key component of mission development. Each NASA center is developing ways to capture (formalize) these new processes and lessons learned from existing processes, but the information is not widely shared, nor well synthesized. The new SSRI Knowledge base tool at the S3VI may develop to fill this need more broadly. Forums like this meeting also can help to serve this need.
	Suggestions or additional comments:	– Gate reviews may not be as useful as advisory reviews in providing effective guidance to projects – Information on management and processes used is often passed down through institutional memory. Establishing a mentoring system could help greatly to increase access to such knowledge for institutions with small or new space programs.

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D4-B3.5	**<u>Challenge</u> or Lesson Learned:**	**No avenues exist for sharing mission experiences and best practices regarding education and training impacts**
	Rationale:	The value of SmallSat and CubeSat missions to provide education and training for both engineers and space scientist cannot be overstated. Yet this beneficial mission outcome is not often captured or communicated.
	Suggestions or additional comments:	– The value of CubeSat missions lies in the breadth the mission team gains from the experience; getting to know how the parts of the system relate to each other is invaluable – These missions often involve small teams, so everyone has to pitch in and wear multiple hats; the "jack-of-all-trades" engineers developed by these missions are versatile and flexible – While these "jack-of-all-trades" engineers do not obtain depth of knowledge, they can often identify breaks in communication between fields – Personnel can be trained later to perform more onerous processes for projects that are more risk averse – CubeSat missions offer unique opportunities for students to publish their first publications—a very important career milestone

7. Afterword

The 2021 NASA SmallSat Virtual Forum expanded the agency's insight into the issues that concern the SmallSat community and provided a wealth of information regarding potential ways that NASA could mitigate these problems. In addition, the forum served as a valuable opportunity for members of the community to exchange ideas, solutions, and lessons learned related to SmallSat development, testing, and operations. NASA will use the information gained from this forum to inform and improve future SmallSat processes, plans, and strategies—all to enable the Agency goal of using SmallSats to achieve transformative science.

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Appendix A. Acronyms and Abbreviations

Acronym	Definition
ACS	Attitude Control System
ACT	Advanced Component Technologies
ADCS	And Control System
AES	Advanced Exploration Systems
AIST	Advanced Information Systems Technology
AO	Announcement of Opportunity
APD	Astrophysics Division
APRA	Astrophysics Research and Analysis
AS3	Astrophysics Science SmallSat Studies
AWS	Amazon Web Services
BB	Baseband
CC	Command and Control
CCSDS	Consultative Committee for Space Data Systems
CDR/SIR	Critical Design Review with the System Integration Review
CLPS	Commercial Lunar Payload Services
CM	Configuration Management
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSLI	CubeSat Launch Initiative
CSR	Concept Study Report
DILT	Day-In-The-Life Testing
DNH	Do No Harm
DOA	Dead on Arrival
DSI	Decadal Survey Incubation
DSN	Deep Space Network
EEE	Electrical, electronic, and electro-mechanical
EELV	Expendable Launch Vehicle
ELFIN	Electron Losses and Fields Investigation
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESD	Earth Science Division
ESPA	Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter
ESSIO	Exploration Science Strategy and Integration Office
ESTO	Earth Science Technology Program
EVC	Earth Venture Class
EVI	Earth Venture-Instrument
EVM	Earth Venture-Mission
EVS	Earth Venture Suborbital
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FRR	Flight Readiness Review
FTE	Full-time Equivalent
GB	Gigabyte
GEVS	General Environmental Verification Standards

GNC	Guidance, Navigation, and Control
GPU	Graphics Processing Unit
GRC	Glenn Research Center
GS	Ground System
GSFC	Goddard Space Flight Center
HEOMD	Human Exploration and Operations Mission Directorate
H-FORT	Heliophysics Flight Opportunities for Research and Technology
H-FOS	Heliophysics Flight Opportunities Studies
HPD	Heliophysics Division
I&T	Integration and Test
ICD	Interface Control Document
IIP	Instrument Incubator Program
IMAP	Interstellar Mapping and Acceleration Probe
IMS	Integrated Master Schedule
ISS	International Space Station
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
KSAT	Kongsberg Satellite Services
LAICE	Lower Atmosphere/Ionosphere Coupling Experiment
LaRC	Langley Research Center
LEO	Low Earth Orbit
LFT	Large File Transfer
LSP	Launch Service Program
MDAO	Multidisciplinary Design Analysis and Optimization
MO	Mission of Opportunity
MOC	Mission Operations Center
NASA	National Aeronautics and Space Administration
NCE	No Cost Extension
NCR	Non-Conformance Reporting System
NEN	Near Earth Network
NOS3	NASA Operational Simulator for Small Satellites
NPR	NASA Procedural Requirement
NRA	NASA Research Announcement
NSF	National Science Foundation
NSN	Near Space Network
NTIA	National Telecommunications and Information Administration
PDR	Preliminary Design Review
PFR	Problem Failure Reporting System
PI	Principal Investigator
PM	Project Manager
POC	Point-of-contact
PSD	Planetary Science Division
QA	Quality Assurance
RF	Radio Frequency
ROSES	Research Opportunities in Space and Earth Science
S3VI	Systems Virtual Institute
SDC	Science Data Centers
SDO	Solar Dynamics Observatory
SE	Systems Engineer

SEMP	Systems Engineering Master Plan
SMA	Safety and Mission Assurance
SMD	Science Mission Directorate
SPENVIS	Space Environment Information System
SPOON	SmallSat Parts On Orbit Now
SPORT	Scintillation Prediction Observations Research Task
SRR	System Requirements Review
SSCG	Small Spacecraft Coordination Group
SSRI	Small Satellite Reliability Initiative
SST	Small Spacecraft Technology
SSTP	Small Spacecraft Technology Program
STMD	Space Technology Mission Directorate
TDRS	Tracking and Data Relay Satellites
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
U.S.	United States
UHF	Ultrahigh Frequency
VADR	Venture-Class Acquisition of Dedicated and Rideshare
VCLS	Venture Class Launch Services
WFF	Wallops Flight Facility